Spectral Analysis of the LUND/DMI Earthshine Telescope and Filters

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1. Spectral Analysis of the telescope and Filters

This section reports the characterization of the spectral response of the filters and knife edge optical densities of the Earthshine telescope and also examines the spectral response of the complete telescope.

1.1 Experimental Setup

An Ocean Optics fiber spectrometer was used to obtain the spectrum of the light through the telescope, using a halogen light source. The spectrometer was placed in the position of the CCD camera, and it was used without the fiber to increase the amount of collected light. Transmission spectra were obtained for different configurations of the Earthshine telescope in order to study the performance of each color filter, as well as of the knife edge filters. The used setup is schematically shown in Figure 1, and the main used elements are the following:

- Earthshine telescope
- Spectrometer: Ocean Optics USB2000[1] (grating groove density of 600nm^{-1})(Ocean Optics)
- Halogen light source
- Circular aperture to decrease light intensity
- Computer for data acquisition (with *OOIBase32* software)

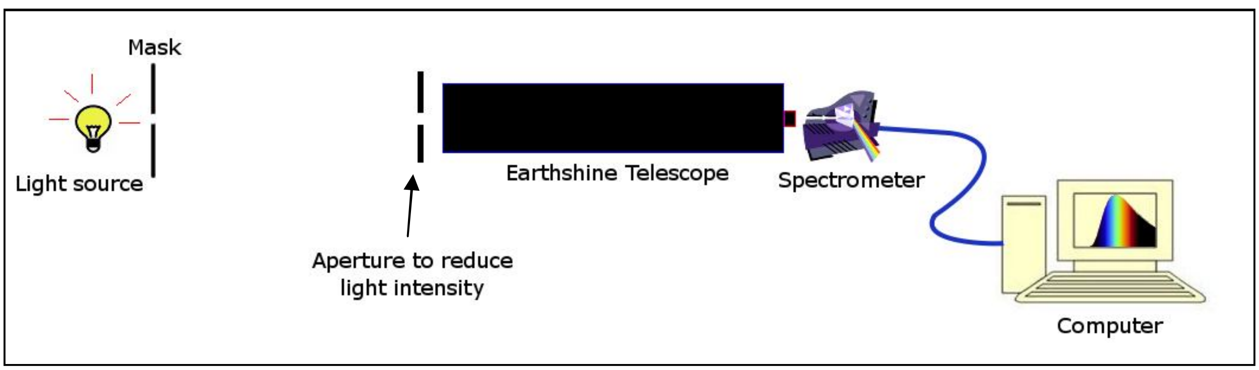

Figure 1 - Experimental setup. The shutter was tested placed inside the Earthshine Telescope.

An analysis of the non-linearity of the spectrometer was performed before the actual measurements of the spectral transmission to ensure correct results.

1.2 Analysis of non-linearity of the Spectrometer:

All CCD detectors suffer some amount of non-linear behavior on their response to the light, and CCD based spectrometers are not an exception. This non-linearity can be corrected if it is measured, and the

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[1] Specifications shown in the Appendix

USB2000 spectrometer has the ability to correct the acquired data using a 7th order polynomial which coefficients can be stored on its EEPROM internal memory. The *OOINLCorrect* software available in the *Ocean Optics* website allows the calculation of these coefficients doing a simple experiment. According to the manufacturer the response without any correction of the USB2000 spectrometer is linear to 93% and linearity >99.8% can be achieved using the correction (Ocean Optics).

The *OOINLCorrect* software analyses the non-linearity of the detection using constant light source intensity while changing the integration time. It measures the response of 9 selected pixels across the detector that have to be selected in the way that they all reach the saturation at the higher integration time limit of the test, and also all they must start with as few as possible counts in the low integration time limit in order to cover most of their dynamic range. The selection of pixels can be done automatically or manually in the software, and their positions will determine the range in wavelength where the correction will be more effective, and also the quality of the correction. The manufacturer affirms that measurements of only 9 pixels are necessary arguing that the nonlinearity of each pixel is identical in one detector (Ocean Optics). The software stores the values of count and counts per second of the 9 pixels for different integrations times, covering the interval between both integration time limits. With the combined collected data of all the pixels, the program fits a 7th order polynomial in the relation between the normalized counts per second and counts, and this polynomial generates a correction factor for the pixels in function of its number of counts. The way to apply the correction is dividing the original numbers of counts by the obtained correction factor for all the pixels.

1.2.1 Calibration Procedure

The first thing to do was to find a suitable light intensity for the experiment. Using the halogen light source, saturation (i.e. 3800 counts) was reached for the pixels between 460nm and 770nm using 500ms of integration time. The stability of the used light source, which was measured with the telescope CCD camera using 100ms exposures, is shown in Figure 2; the spectrum the light source is shown later in Figure 10. The exposures times for the test were chosen in order to obtain the biggest amount of saturation at the high integration time level while at the same time produce relatively few counts at the low integration time level; the selected low integration time level for the calibration measurements was 10ms producing around 300 counts above the dark level at the higher peak of the light source spectrum.

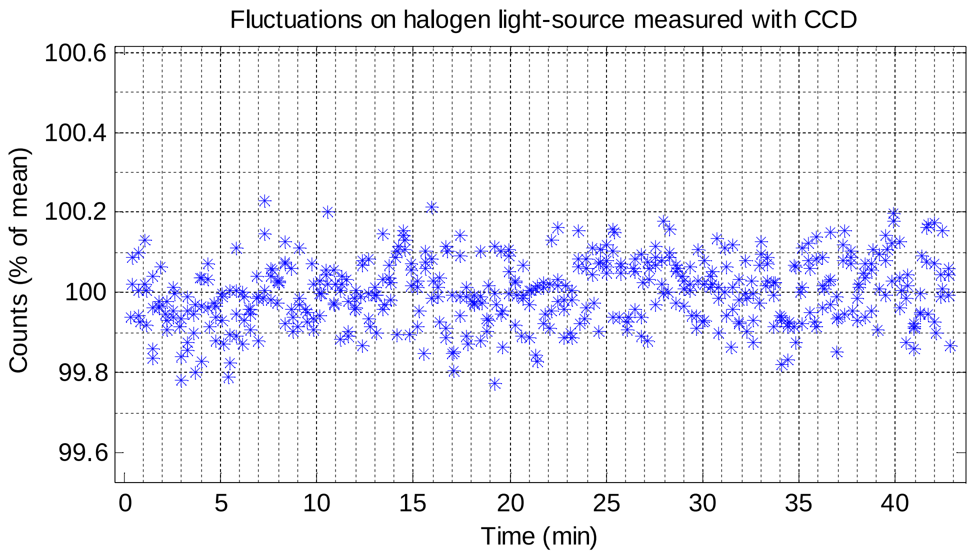


Figure 2 - Stability of the used halogen light-source measured using Andor CCD camera.

The experiment was repeated many times, testing different values for the integration time limits and for the integration incremental step. Also different pixel selections were tested. In this way many calibration polynomial candidates were obtained.

A second experiment was performed to check the quality of the candidates. Spectra of the light source were taken at different intensities changing the integration time using the *OOIBase32* acquisition software with the non-linearity correction turned off. Afterward, the candidate calibrations were applied to the data using a code in MATLAB™, and then ratios between the spectra of different integration times were calculated and normalized. The obtained ratios are correlated with the goodness of the calibration candidates, and for ideal perfect correction this ratio should be the unity for all wavelengths.

1.2.2 Results

As was previously mentioned, many similar but different calibration polynomials were obtained using the *OOINLCorrect* software. An example of Nonlinearity Correction Report is shown in Figure 3. It shows the acquired data points, the regression results of the fitted 7th degree polynomial, and the processed output after the application of the calibration.

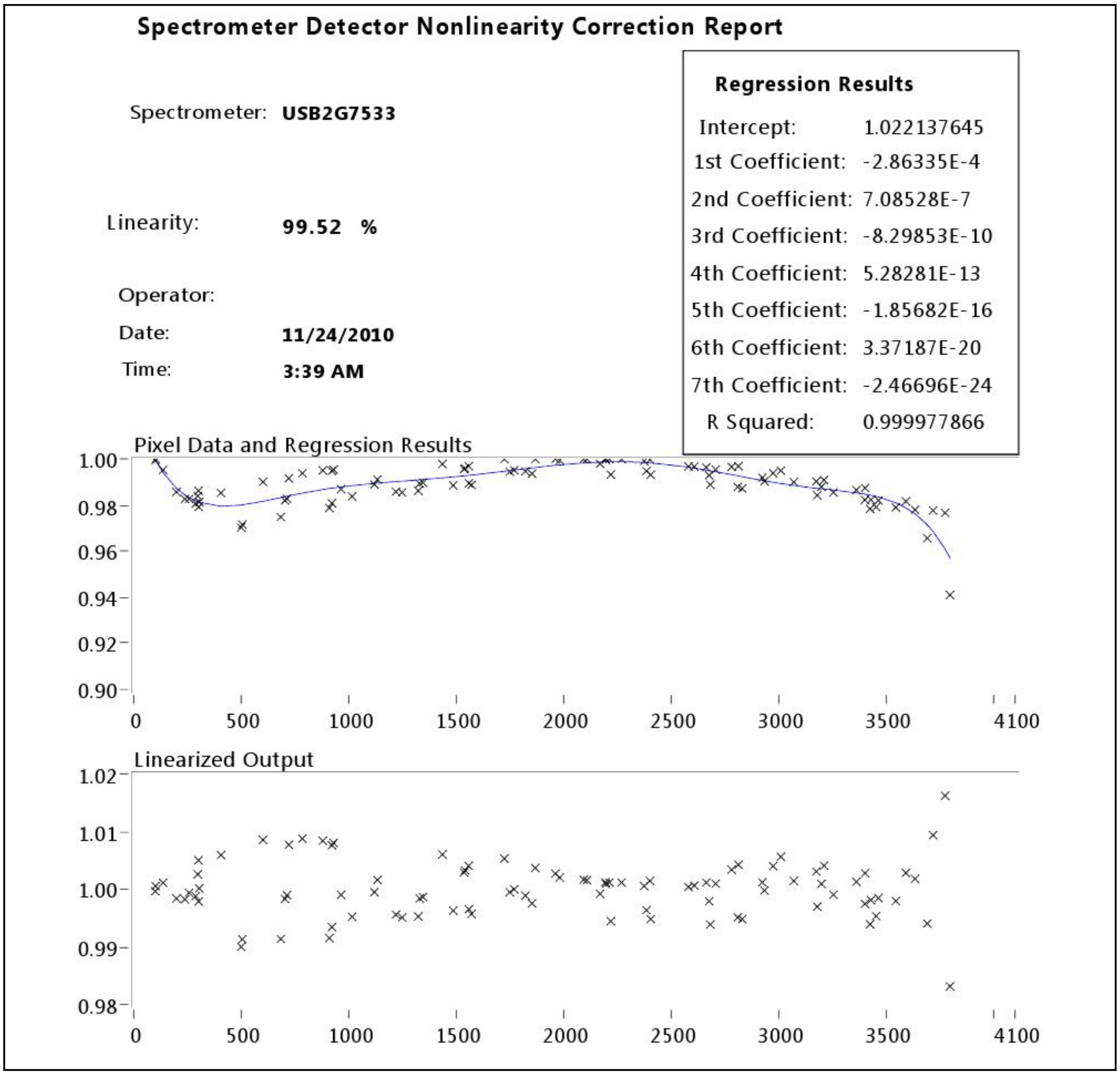


Figure 3 - Example of Non-linearity calibration report generated with the *OOINLCorrect* software. The settings for this example were high integration level of 900ms, low integration level of 10ms and integration step of 20ms. The y-axis values are the normalized counts per second. The x-axis values are the counts. This example was the best correction obtained with the software.

Unfortunately the calibration software did not produce a stable output, and many different polynomials of different characteristics were obtained repeating the procedure.

The second experiment was made to find the most suitable calibration for our purpose. It was to compare spectra of the same light-source taken with different exposures. Figure 4 shows the obtained ratios (normalized) between a short and a long exposure for three different calibration settings: no calibration, typical obtained calibration, and best found calibration. The peak value of the spectra was 90 counts for the short exposure, and 3220 for the long exposure. The normalization was done making equals the areas under the spectra before taking the ratios.

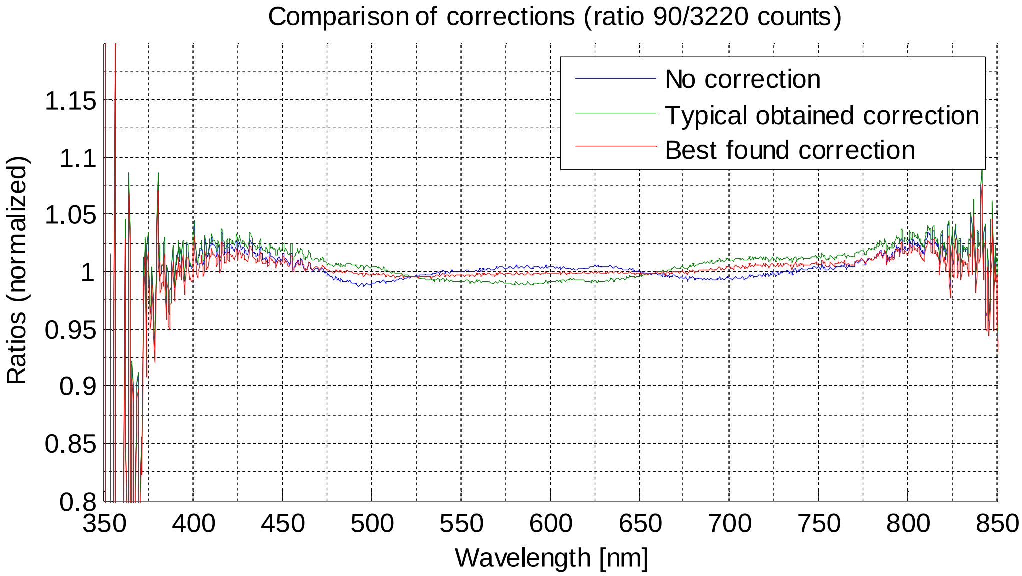


Figure 4 - Ratios between the spectra of same light source at different exposures. Ratio *90/3220* means a short exposure spectrum with a maximum value of 90 counts divided by long exposure spectrum with maximum value of 3220 counts.

The *90/3220* ratio shown in Figure 4 was the one that covered the widest dynamic range of the detector, because the spectrum with maximum at 90 counts was obtained using the minimum possible exposure in the spectrometer, 3ms. The level with maximum at 3200 counts was chosen because it was a high value but far enough of the actual saturation level (3800 counts) to avoid undesired effects; it was achieved using 100ms of integration time. The light intensity used was the same chosen for the subsequent transmittance measurements, the highest attainable intensity.

In the experiment more intensity levels were measured using exposures of 12ms, 25ms and 50ms corresponding 380, 790 and 1590 count for the maximum peak, respectively.

It was found that for the ratios for the uncalibrated data, the worst was the ratio *90/3220* as expected and shown in Figure 5.

The best calibration was obtained slightly modifying in MATLAB the polynomial of the measured candidate with better performance in the ratio test (shown in Figure 3) giving special importance to the ratio *90/3220* because the measurements of transmission using the optical densities will produce weak spectra with few counts. The ratio test result of the best correction is shown in Figure 6. The coefficients of this correction are shown in Table 1.

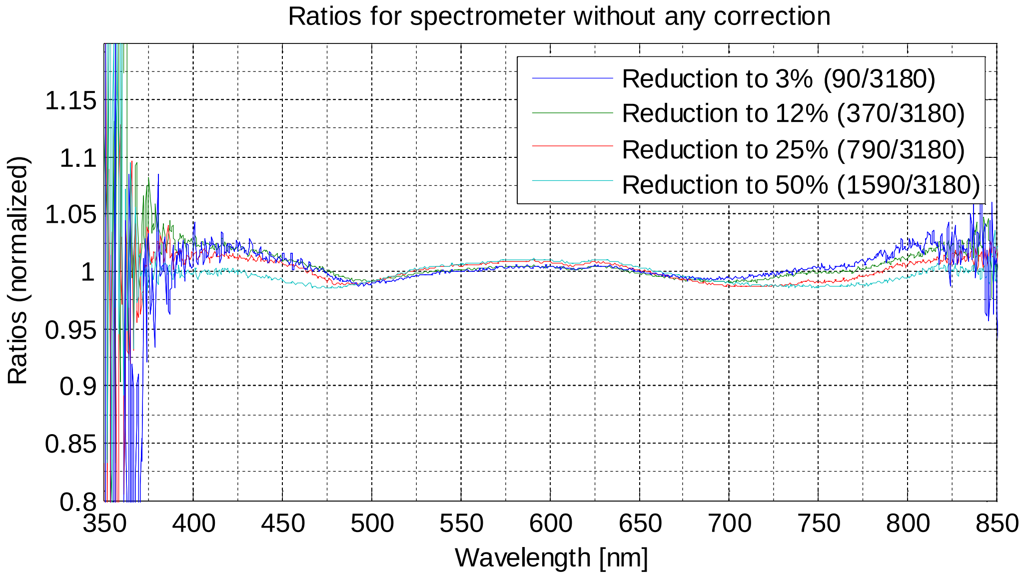


Figure 5 - Ratios between spectra of the light source at different exposures without applying any correction. The differences between the amplitudes of the spectra are also shown as percentages of reduction of the high level.

Best obtained calibration polynomial

P0	P1	P2	P3
9.87098E-01	-8.67736E-05	2.74189E-07	-3.58113E-10
P4	**P5**	**P6**	**P7**
2.48280E-13	-9.35350E-17	1.79526E-20	-1.37379E-24

Table 1 - Best obtained correction polynomial coefficients: P0 is the constant term; P1 is the term associated with first power of x, and so on. The input of the polynomial is the number of counts of a pixel, and the output is the correction factor needed for that pixel.

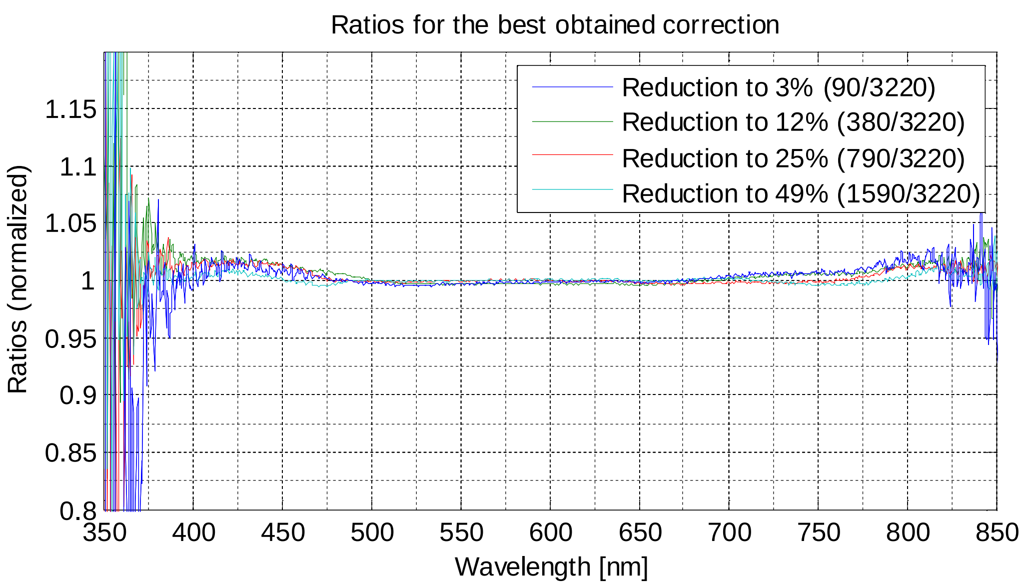


Figure 6 - Ratios between spectra at different exposures of the light source applying the best obtained correction. The differences between the amplitudes of the spectra are also shown as percentages of reduction of the high level.

Table 2 summarizes the data shown in Figure 5 and Figure 6 in terms of percentages of estimated linearity per wavelength interval. Those values were calculated using the average trend of the curves discarding the contribution of the high frequency noise peaks.

Interval [nm]	Uncalibrated	Calibrated
400 to 830	96%	98%
470 to 750	97%	99%
500 to 700	98%	99%

Table 2 – Percentages of estimated linearity

The same data from Figure 5 and Figure 6 was rearranged in function of the counts of the high level spectrum, using the spectral data of that level to associate wavelengths to counts. This led to Figure 7 and Figure 8.

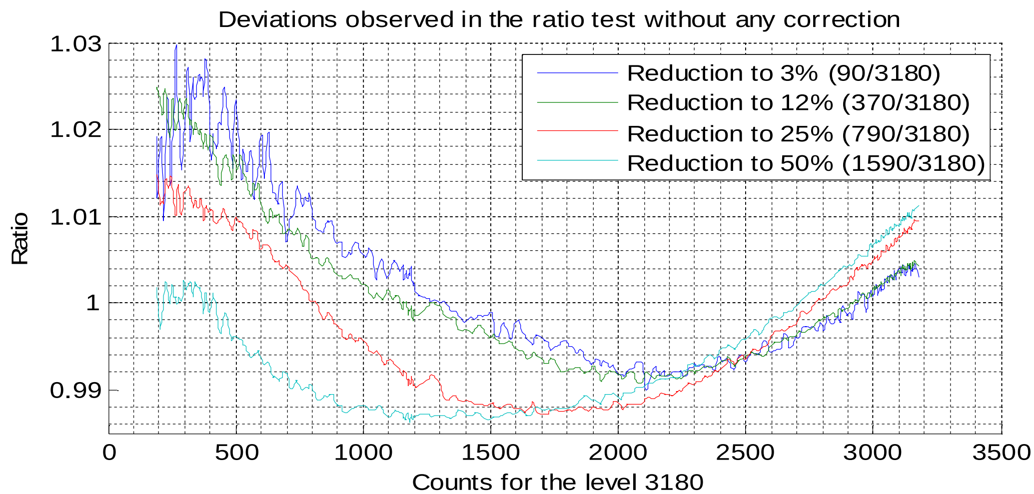


Figure 7 – The data from Figure 5 rearranged using the collected spectra to obtain this plot of ratios versus counts for the uncalibrated data.

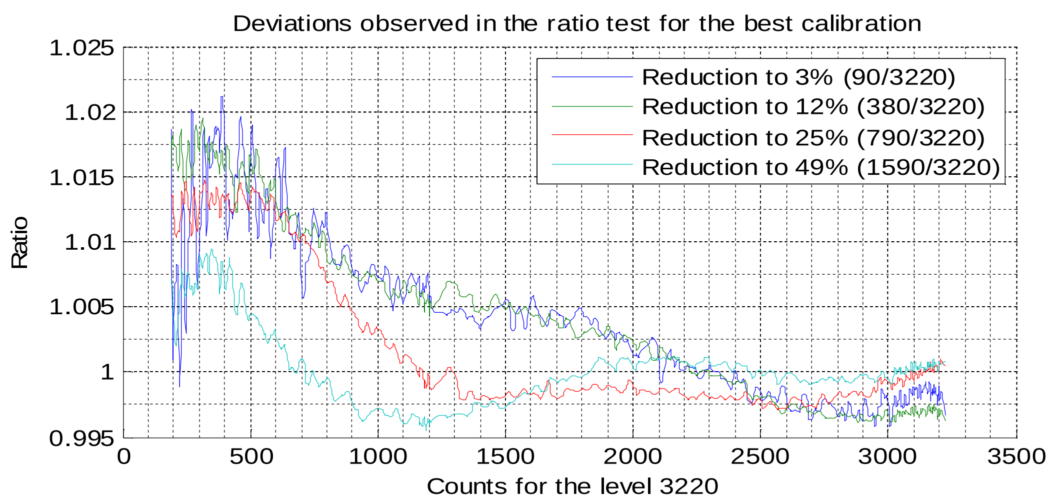


Figure 8 - The data from Figure 6 rearranged using the collected spectra to obtain this plot of deviation versus counts for the best calibration. Note that the high level slightly changed its counts from 3180 to 3220 due the calibration effect.

1.2.3 Discussion

As the knife edges density filters will reduce the intensity of the light through the telescope about 3 or 4 orders of magnitude, it is very important that response of the used spectrometer be as good in order to get reliable transmission spectra. Hence, a calibration of the response of the spectrometer to the light was performed.

Non-linearity calibration polynomials for the spectrometer were obtained using a computer program provided by the manufacturer. However the resulting polynomials showed significant variations.

One reason of this variability in the polynomials was the use of different settings in the software, specially the pixel selection. Another explanation can be changes in unmonitored the experiment variables like small fluctuations in the light source intensity or change in the spectrometer CCD detector temperature. Also the photon noise could be an important factor that affected the measurements for the low intensity measurements.

The data of the second experiment was used to determine which calibration produced a better response analyzing the result of each calibration at different intensity levels. The comparison between the highest and lowest levels (i.e. ratio *90/3220*) is of special interest because it covers the levels needed to measure the optical densities of the Earthshine telescope, and great improvement was achieved for this ratio (from 3% to 1% of deviation from linearity in the range 470nm to 750nm).

The results in Table 2 show the improvement in linearity considering all the ratios between different levels. Basically the error is reduced to its half. However there is another benefit of the obtained calibration. Comparing Figure 5 and Figure 6 we can observe that the shapes of the calibrated ratios are more planar and more similar among themselves, and this will produce more reliable spectral shapes.

The shapes of the curves in Figure 7 and Figure 8 show more clearly the effect of the calibration. The original performance of the spectrometer show non-linear behavior through all the counts range. After the calibration the non-linear behavior is strongly reduced for the higher part of the dynamic range of the spectrometer. This means that for transmittance measurements the linearity will be better for the regions where the reference light-source has higher counts; it will be better than 99% for regions with more than 1000 counts at the reference. Figure 7 and Figure 8 also show that the ratios for the highest counts are closer to the unit if the calibration is used, indicating that the used normalization criterion of equal areas and the criterion of normalization using the maximum values are more consistent.

As the calibration of the spectrometer was performed offline applying the correction to the spectra using a MATLAB code, further improvements to the non-linearity correction can be done to increase the accuracy of the spectral measurements. This improvement could be done using a different light source with wider spectrum, or modifying manually even more obtained polynomial using MATLAB checking the result with the intensity ratio test.

1.3 Spectral measurements

Spectra of light thought the telescope were acquired using the setup shown in Error! Reference source not found., for different configuration of telescope: clear window (no filter applied), color filters and knife edge filters. The tested color filters were: JOHN-V-25, JOHN-B-25, Shortpass filter 750nm, Longpass filter 750nm; all from *Asahi Spectra Co*(Asahi Spectra USA Inc.). The tested knife edges density filters have nominal optical densities 3.5, 3.75 and 4 and were manufactured by *Ferroperm Optics A/S*(Ferroperm Optics A/S) specifically for the Earthshine Project.

In addition, the spectrum of the light source was also measured without the telescope to examine the transmittance spectral curve of the complete telescope (losses introduced by the lenses).

1.3.1 Procedure

Before the test, the positions of the filters and knife edges were checked with the CCD camera. The telescope control software was configured to be capable of cover completely the field of view with coated part of the knife edges density filters.

First of all, the light source and spectrometer were turn on and one hour was waited to obtain stabilization of temperature in both devices. This was checked in the spectrometer monitoring the stabilization of the dark level.

Secondly, spectra of the clear window were taken using a small aperture placed in front of the telescope in order to reduce the light intensity. Spectra were acquired using the following settings: 3ms and 2000 samples averaged, 12ms and 500 samples averaged, and 100ms and 100 samples averaged to obtain maxima values of 300, 600 and 3500 counts respectively. These spectra were used to check the calibration.

After that, the small aperture in front of the telescope was removed and the reference spectrum of the clear window was measured using 7ms of exposure and 1000 samples averaged obtaining maximum about 3200 counts including dark. The experiment had to be repeated afterwards to measure the OD3.75 that wasn't available at the first time, and in this second opportunity the maximum of the reference was near 2990 counts. The dark level was about 200 counts in both occasions.

Next the spectra of the knife edges were acquired using 4s of exposure and 10 samples averaged. This produced about 750, 500 and 350 counts at the peak for the OD3.5, OD3.75 and OD4 respectively. References were taken repeatedly to check for variations in the light-source.

Later, the spectra of the color filters were measured using 7s of integration time and 1000 samples averaged.

Finally, the spectrum of the light source was measured directly, without the telescope, using 4s of exposure and average of 10 samples. This produced a spectrum with maximum about 2000 counts including the dark contribution.

1.3.2 Results

The spectral measurements of the light source using the attenuator were done to test the non-linearity calibration at the condition used for the transmittance measurements. The integration times were selected to obtain similar count values to ones obtained with optical densities of the knife edges, and ratios were calculated again between these spectra of same shape but different counts levels. Figure 9 shows the measured deviations using the chosen calibration.

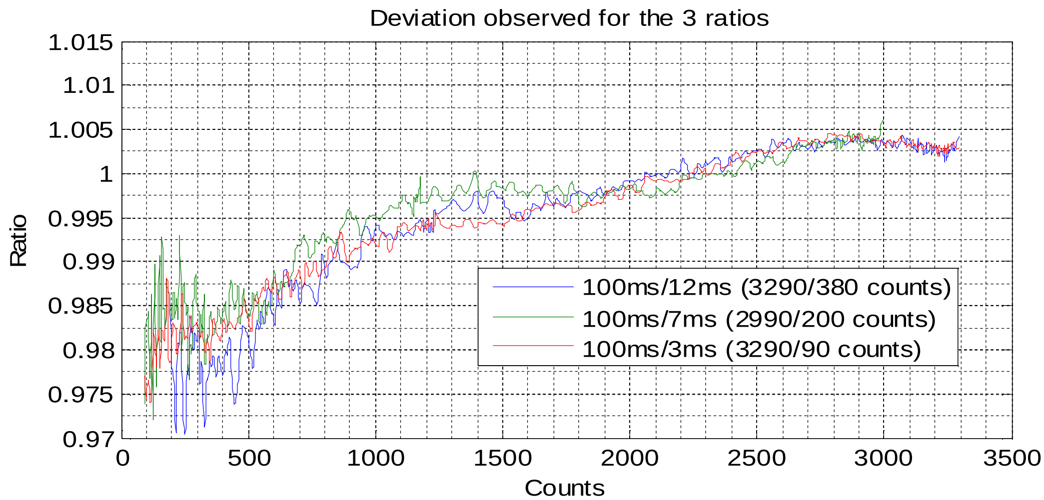


Figure 9 – Deviations obtained for ratio between levels high number of counts and count level similar to the expected for the optical densities of the knife edges

The deviation curves are consistent with the previous calibration results, and they could be used to correct even more the measurements, and it effect was tested. However the result of this new correction only shifts the resulting curves about 0.01 OD in some areas. As this new correction didn't shown any appreciable improvement in the transmittance curves of the knife edges, it wasn't considered in the measurements of the filters.

The transmission of the color filters was obtained using the measured spectra amplified by their exposure times, and then calculating the ratios between the spectra of each filter and its amplified reference. The obtained transmission curves are show in Figure 12, Figure 13, Figure 14, and Figure 15, indicating with red the discarded part. This discarded zone was not reliable because the intensities of the sample and the reference were both small together (sample less than 5 counts and reference less that 100 counts) or because the reference was too weak (less than 5 counts).

The transmission curves of the knife edge are presented in Figure 16, Figure 17 and Figure 18 as optical densities (i.e. logarithmic scale). The spectrum of the light source used for the experiment is shown in Figure 10.

The estimated spectral shape of the transmission through the Earthshine telescope with no filters is shown in Figure 11. The 100% transmission level is arbitrary in this case, and the data above 800nm was discarded because it suspicious rising behavior.

Full size plots of the obtained transmission curves of the filters can be found in the Appendix.

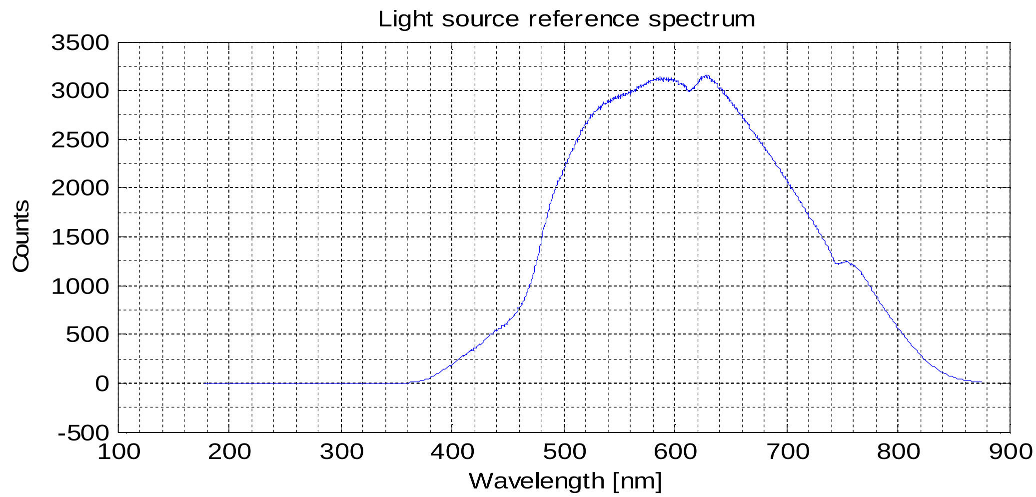


Figure 10 – Spectrum of the halogen light source used as reference for the transmission measurements and in the calibration.

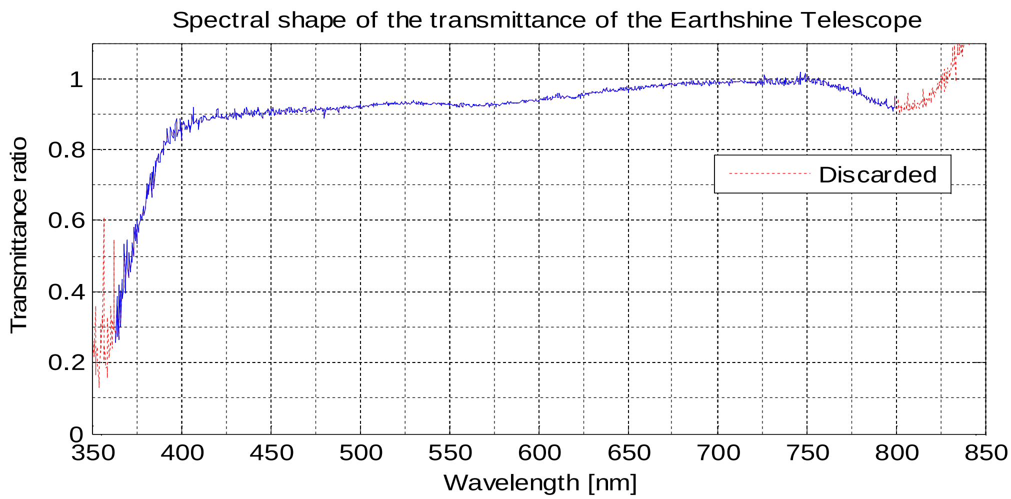


Figure 11 – Estimated spectral shape of the transmittance of the Earthshine telescope with no filters.

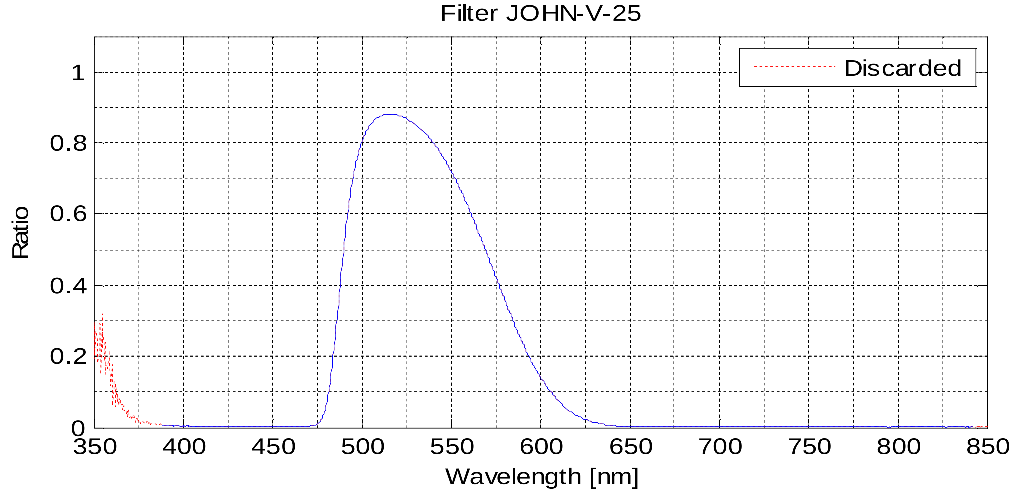


Figure 12 – Spectral transmittance of the JOHN-V-25 filter.

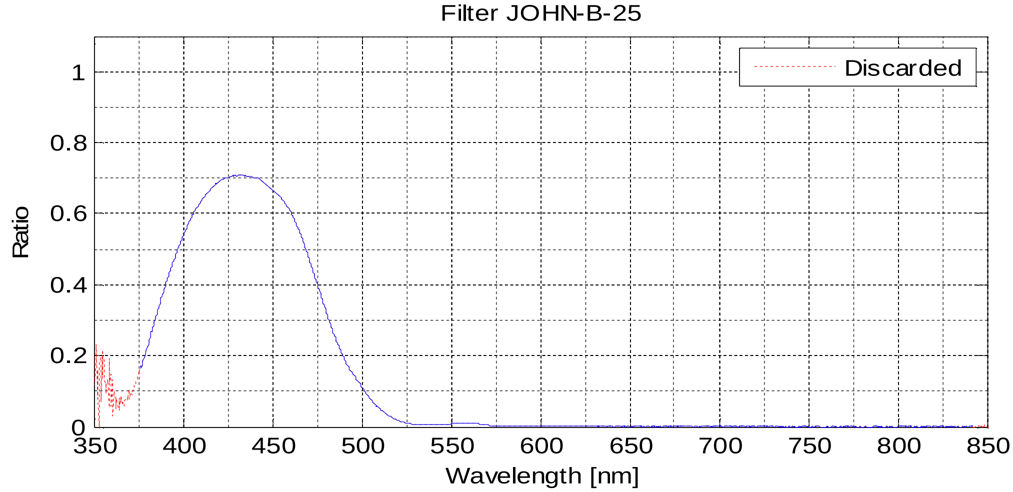


Figure 13 – Spectral transmittance of the JOHN-B-25 filter.

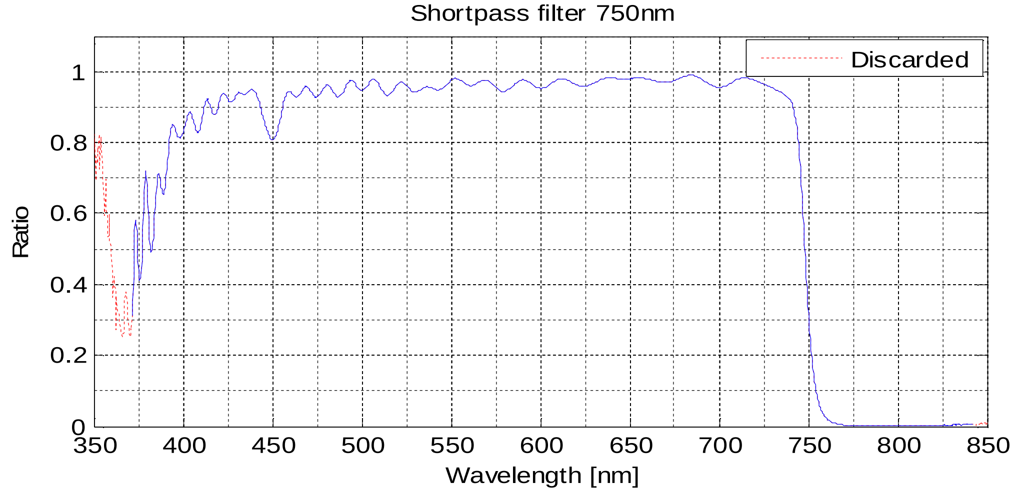


Figure 14 – Spectral transmittance of the Shortpass filter.

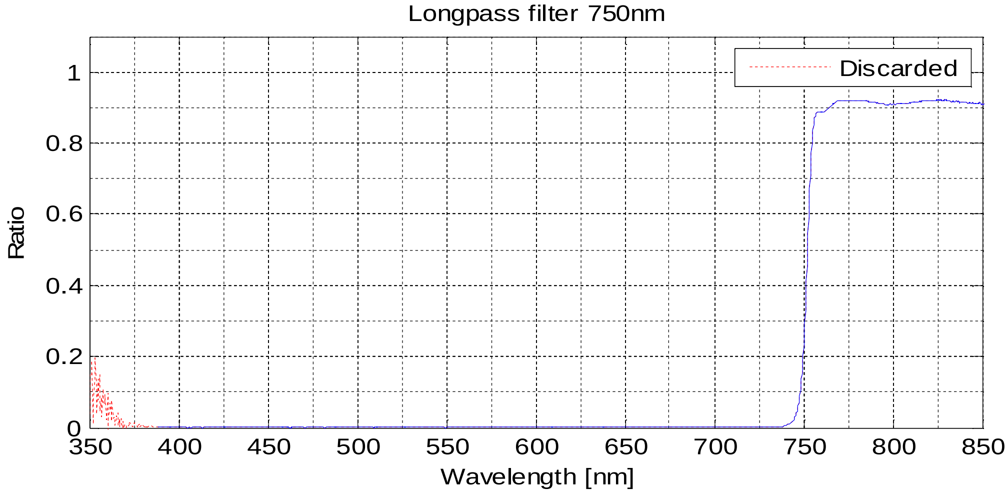


Figure 15 – Spectral transmittance of the Longpass filter.

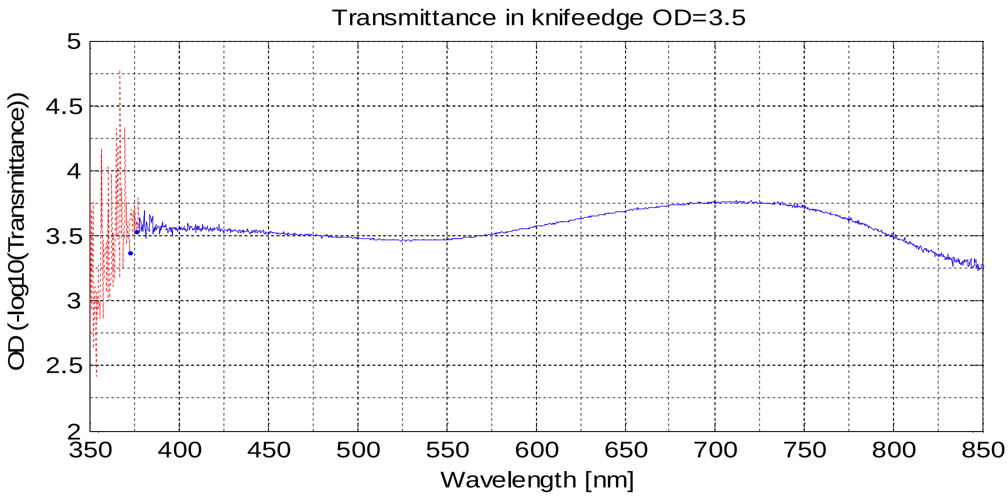


Figure 16 – Spectral transmittance of the knife edge OD=3.5 covering all the field of view.

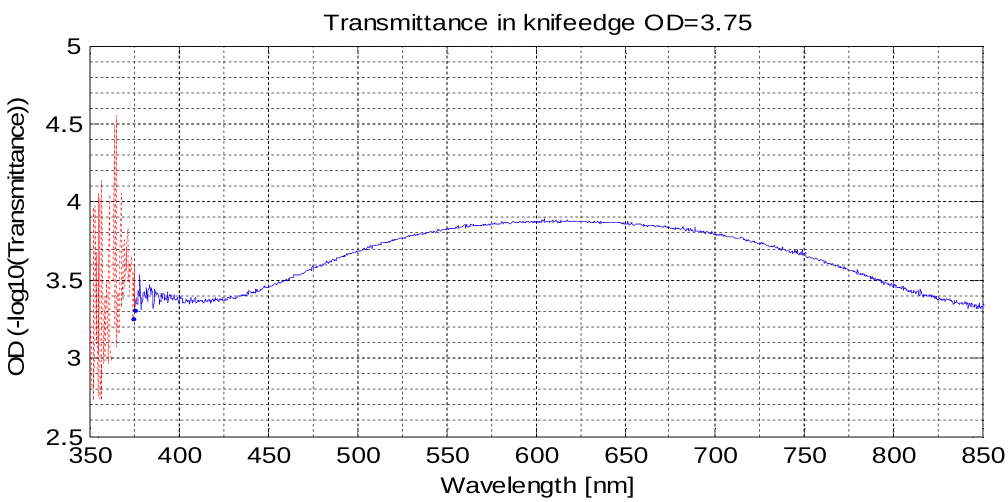


Figure 17 – Spectral transmittance of the knife edge OD=3.75 covering all the field of view.

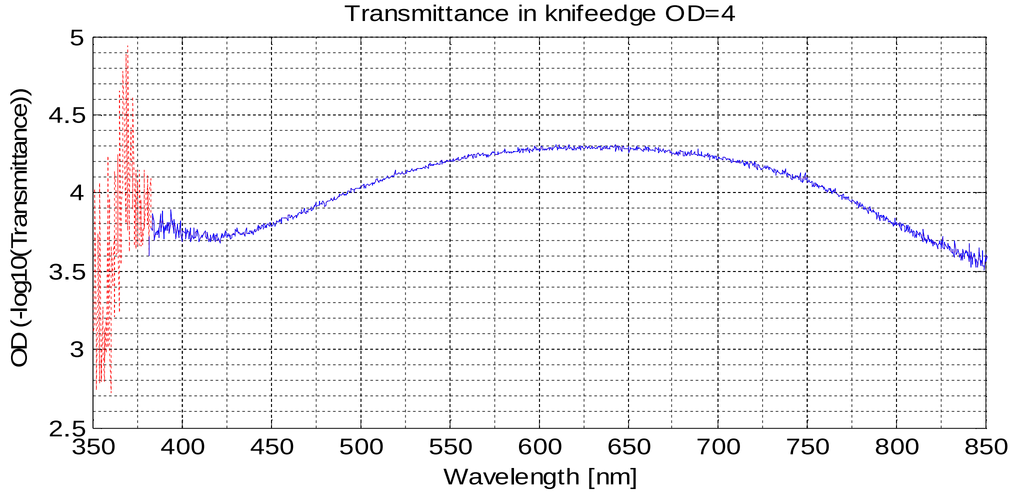


Figure 18 – Spectral transmittance of the knife edge OD=4 covering all the field of view.

1.3.3 Discussion

The obtained transmittance curves were compared with the provided by the manufacturers of the filters. The match is near perfect for the shapes and the values for the color filters. For the Shortpass filter the absorption peak near located at 450nm in the measured transmittance seems to be shifted few nanometers in the manufacturer datasheet; also the few values below 375nm seems to be over estimated.

For the knife edges the situation is different. The measured spectral transmittance of the knife edge with OD=3.5 is very different from the specified by the manufacturer, because it shows a rather planar zone from 375nm to 700nm that is not present on the manufacturer datasheet. This result was verified doing a second measurement with a different sample of the same KEDF, obtaining the same spectrum. However, the measured transmittance curves of the other two knife edges are very similar to the specified, with the difference that the measured curves seem to be slightly narrower, compressed from the right side 40nm approximately.

The differences between the measured data and the manufacturer data sheets can be described as following. For the differences observed in the color (Shortpass) filter, the most probable is that the obtained linearity exhibited in Figure 8 is not good enough for low count levels, and this will be especially important at the wavelengths where sample and reference have low but different counts levels (see Figure 10 and Figure 14). This could be improved using a better light source with more radiation towards the UV region, or enhancing the calibration reducing even more the non-linearity.

The result showing the transmission through the Earthshine telescope without any filter is the mostly a qualitative result. Because of the difficulty in measuring the absolute light level of light source itself and through telescope the transmission curve has been scaled to 100% at maximum transmission. It shows a transmittance above 90% for all the wavelengths above 450nm, and a decrease transmission going to shorter wavelengths leading to a strong reduction in the UV region as expected due the anti-reflection coating on the telescope lenses.

The transmission of the JOHN-V filter is mainly between 480nm and 600nm, with maximum value of 89% at 516nm and its FWHM is 84nm. Its transmission is mainly in the green and yellow color ranges of the visual spectrum.

The transmission of the JOHN-B filter is for smaller wavelengths, mainly between 370nm and 500nm. Its maximum transmission is 71% at 432nm, and its FWHM is 91nm. Its transmission is mostly complementary to the one of the JOHN-V filter, mainly in the violet and blue color ranges.

The Shortpass filter is broadband, with transmission higher than 80% between 393nm and 744nm. It has a sharp cut off frequency at centered at 748nm, and its transmittance is lower than 2% for wavelengths higher than 761nm. Its spectral shape has many fringes, and the biggest one is located at 450nm. Basically this filter allows the transmission of the visual spectrum, blocking the infrared component.

The Longpass filter is the complementary to the Shortpass, with a sharp cut-off frequency centered at 752nm. Its transmission is higher than 88% for wavelengths longer than 757nm, and shorter than 2% for wavelengths shorter than 744nm; its shape has not as many fringes as the Longpass filter. This filter only allows the transmission of infrared light.

The spectral shapes of the KEDF are much softer. Instead show rather sharp spectral features, they exhibit slow tendencies to absorb more between 550nm and 700nm for the optical densities 3.75 and 4, and between 650 and750 for optical density 3.5. The difference between the maximum and minimum transmission is approximately one optical density for all the KEDFs.

2. Conclusions

The spectral transmittance of all the color filters and knife edge density filters (KEDF) of the LU/DMI Earthshine Telescope were measured using the USB2000 spectrometer. A non-linearity calibration was done for the spectrometer prior to the spectral measurements to reduce its associated error. Experimentally was determined that the original linearity of the spectrometer was 96%, and it was increased to 98%. Furthermore 99% of linearity was achieved with the calibration for the wavelength range between 470nm and 750nm.

The non-linear calibration was obtained after testing different candidates, selecting the one that produced best performance taking in consideration that the calibration needed to be valid for a high dynamic range in order to get reliable spectra of the KEDFs. The 98% of linearity was attained even for a reduction to the 3% of the reference spectrum.

It was found a great agreement between the measured transmission spectra and the filters specifications. The only filter that shows a discrepancy with the manufacturer datasheet was the KEDF with optical density 3.5. The measurement was repeated using another sample of the same filter, and the same spectral curve was obtained. As the spectral curves of the others KEDF exhibit good agreement with the specifications, probably the coating process suffered some modification.

The knowledge of the shape of the KEDF spectra is important because it is needed to correct its effect on the observations of the bright side of the moon. If it is not considered, the spectral-photometric data collected using the Lund Mode will be strongly biased.

In contrast, the spectral curves of the color filters are needed for all the modes of the Earthshine telescope, to produce accurate spectral-photometric measurements.

Different information about the Earth's albedo can be extracted using the available color filters. The cut-off frequency of the filters Shortpass and Longpass is near to the "vegetation red edge" present in green vegetation (Thejll, P., Flynn, C., Gleisner, H. and Mattingly, A., 2008), thus these two filters can be used to measure a vegetation index that can provide information about the percentage of vegetation present in the Earth's albedo. Also the JOHN-B and JOHN-V filters could be used to monitor the amount of reflection in the oceans present in the Earth's albedo.

Concerning the spectral shape of the whole Earthshine telescope, it mainly shows that it has low transmission below 400nm in the UV region. This was expected because the VIS-NIR anti-reflection coating applied on the telescope lenses, which is designed to have optimum transmission at the visible and near infrared regions but not for the ultraviolet.

About the accuracy of the measurements, the results of the tests comparing spectra of the light-source at different exposures show that the obtained non-linearity for transmittance measurements is 2% for all the wavelengths, and 1% between 470nm and 750nm. The stability of the used light-source was about 0.4%.

About the spectral characterization of the filters, the 1% of accuracy reached is enough for the spectro-photometric analysis of the albedo for all the operating modes of the telescope. However for the Lund Mode it is needed a more precise measurement the transmittance of the KEDFs, which also includes an analysis of the spatial uniformity of the filters. This is needed because the KEDFs are located in the first image plane of the telescope, thus the uniformity of the filters will be reflected on the acquired images, and this analysis must have an accuracy of 0.1%.

Appendix -

Ocean Optics USB2000 specifications(Ocean Optics)

USB2000 Specifications

The following sections provide specification information for the CCD Detector in the USB2000, as well as the USB2000 Spectrometer itself.

CCD Detector Specifications

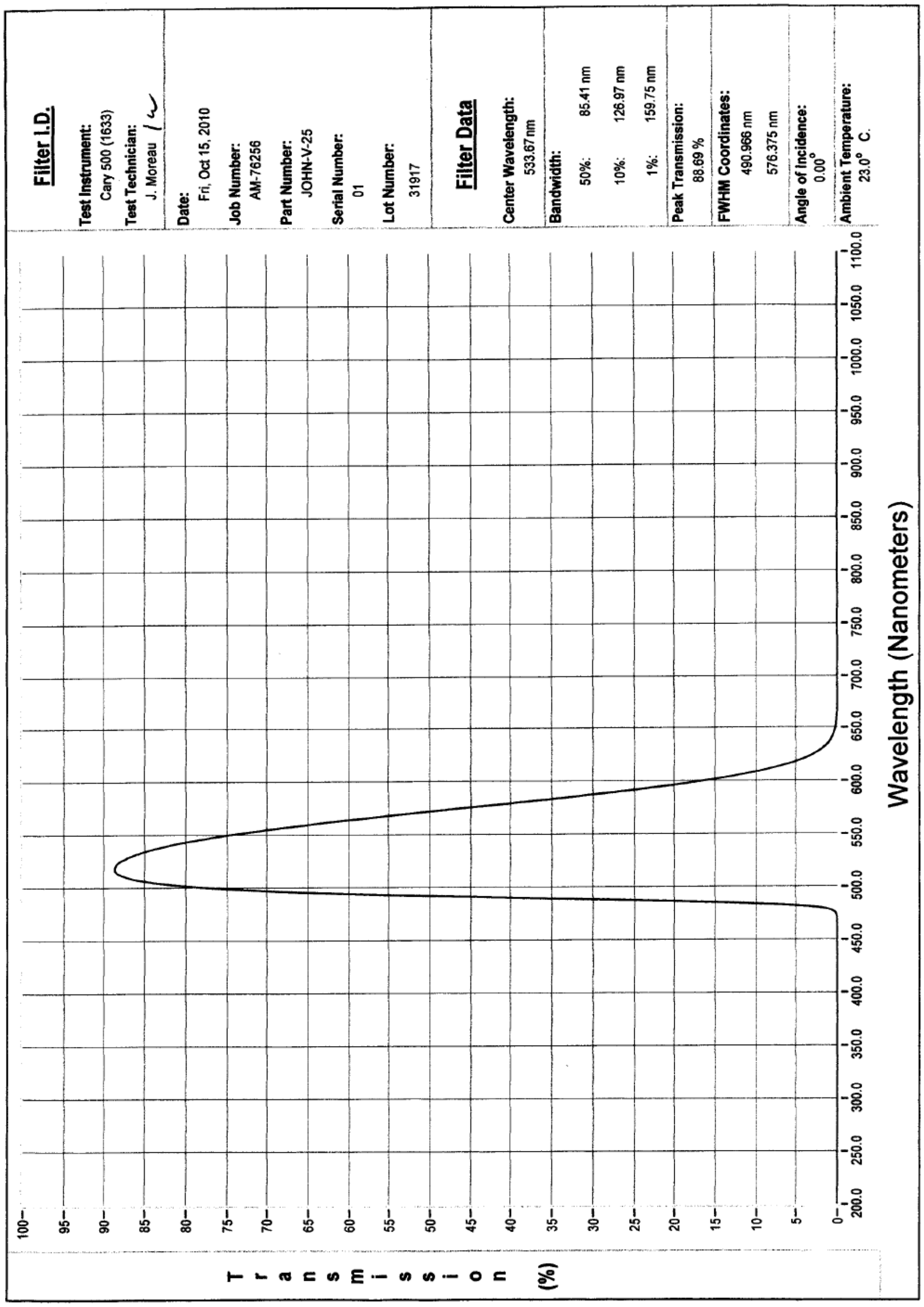
Detector:	Sony ILX511 linear silicon CCD array
Number of elements:	2048 pixels
Pixel size:	14 µm x 200 µm
Pixel well depth:	62,500 electrons
Signal-to-noise ratio:	250:1 (at full signal)
A/D resolution:	12 bit
Dark noise:	2.5 RMS counts
Corrected linearity:	>99.8%

USB2000 Spectrometer Specifications

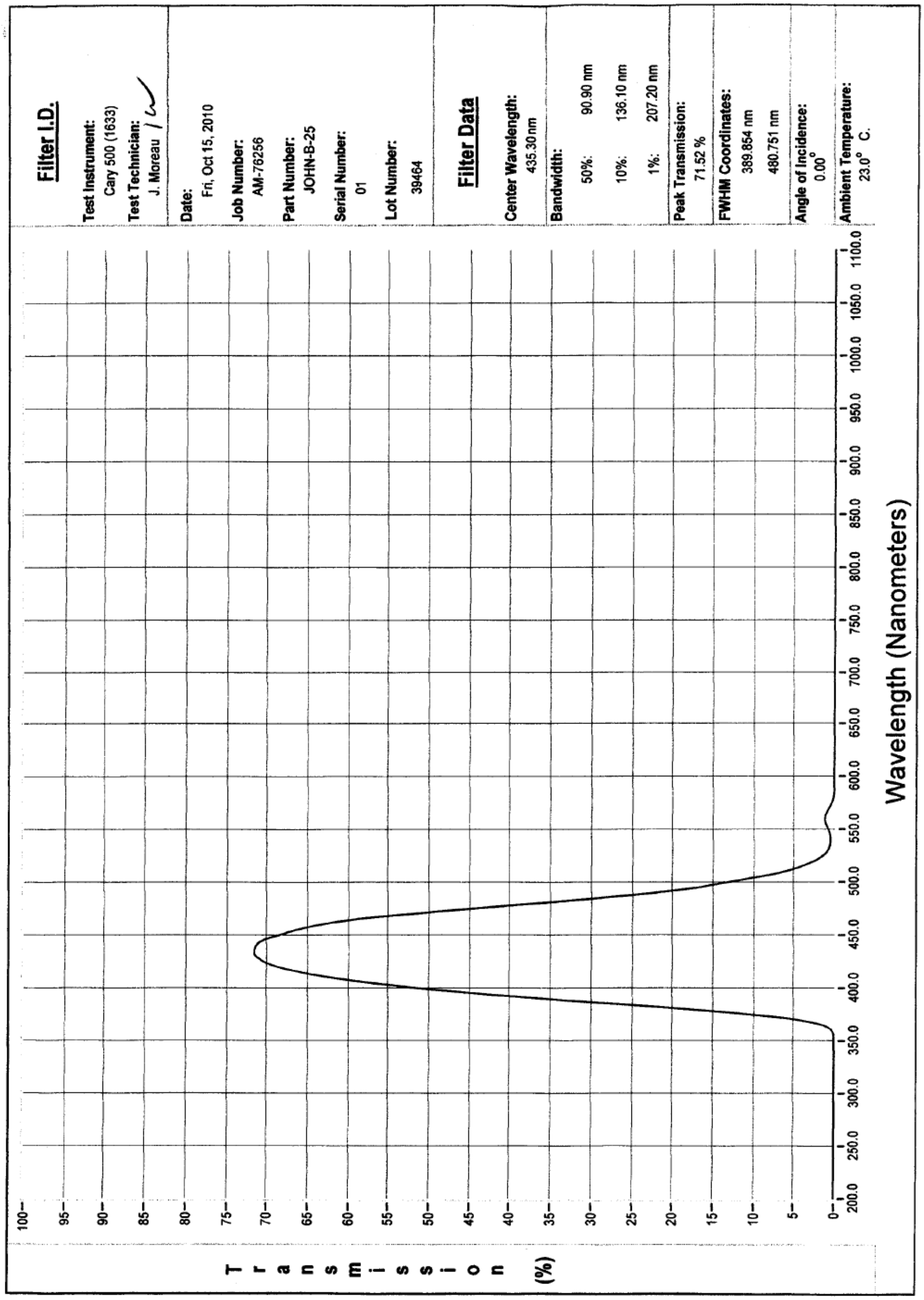
Dimensions:	89.1 mm x 63.3 mm x 34.4 mm
Weight:	190 g (without cable)
Power consumption:	90 mA @ 5 VDC
Detector range:	200-1100 nm
Detector:	2048-element linear silicon CCD array
Gratings:	14 gratings; UV through Shortwave NIR
Entrance aperture:	5, 10, 25, 50, 100 or 200 mm wide slits or fiber (no slit)
Order-sorting filters:	Installed longpass and bandpass filters
Focal length:	f/4, 42 mm (input); 68 mm (output)
Optical resolution:	~0.3-10.0 nm FWHM (depending on grating and size of entrance aperture)
Dynamic range:	2 x 10^8 (system); 2000:1 for a single scan
Stray light:	<0.05% at 600 nm; <0.10% at 435 nm; <0.10% at 250 nm
Sensitivity (estimate):	400 nm – 90 photons/count; 600 nm – 41 photons/count; 800 nm – 203 photons/count
Fiber optic connector:	SMA 905 to single-strand optical fiber (0.22 NA)
Data transfer rate:	Full scans into memory every 13 milliseconds
Integration time:	3 milliseconds to 65 seconds
Fiber optic connector:	SMA 905 to single-strand optical fiber (0.22 NA)
Operating systems:	Windows 98/Me/2000/XP when using the USB interface on a desktop or notebook PCs Any 32-bit Windows operating system when using the serial port on desktop or notebook PCs Windows CE 2.11 and above when using the serial port on palm-sized PCs

Appendix - Filter specifications

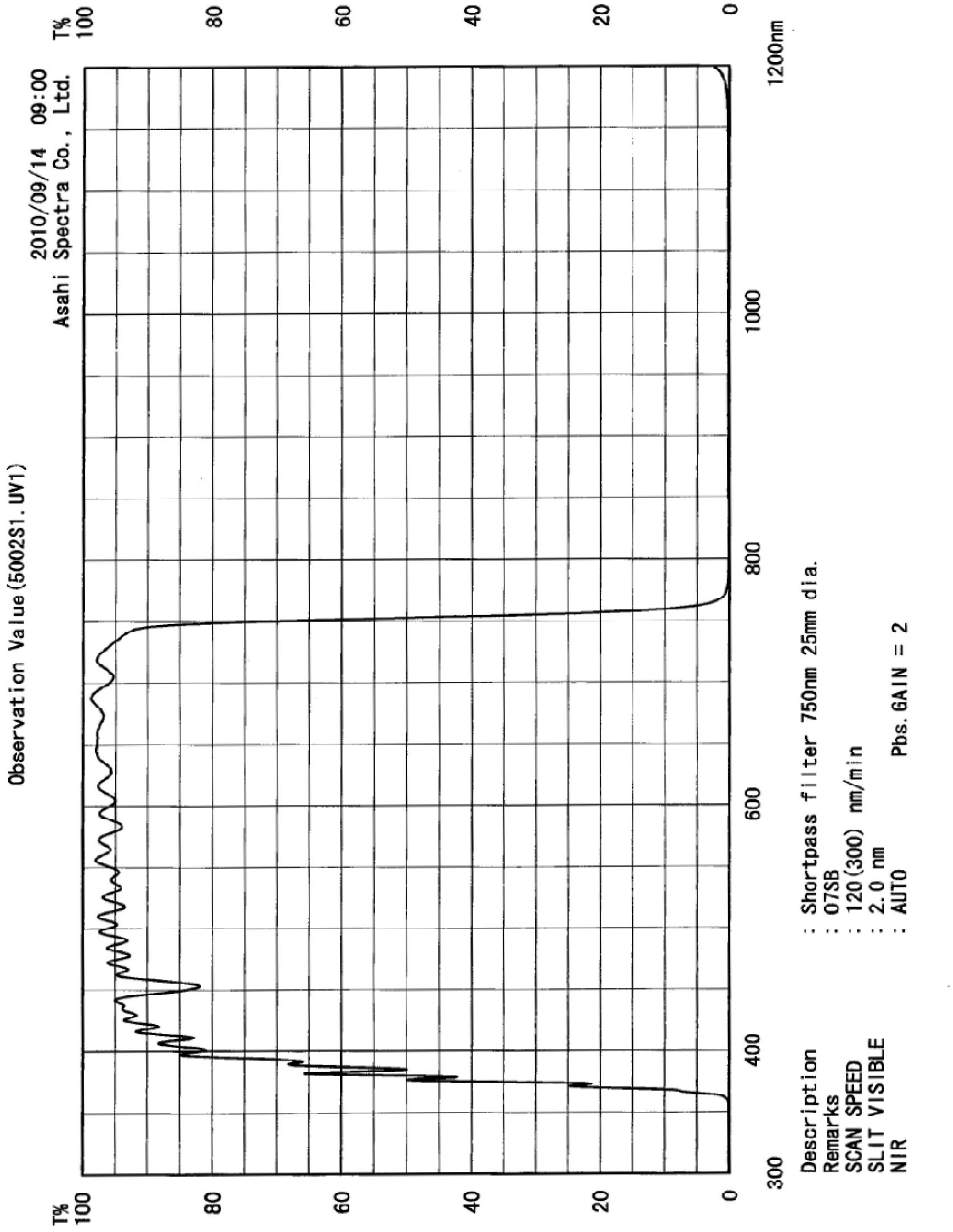
JOHN-V-25 filter



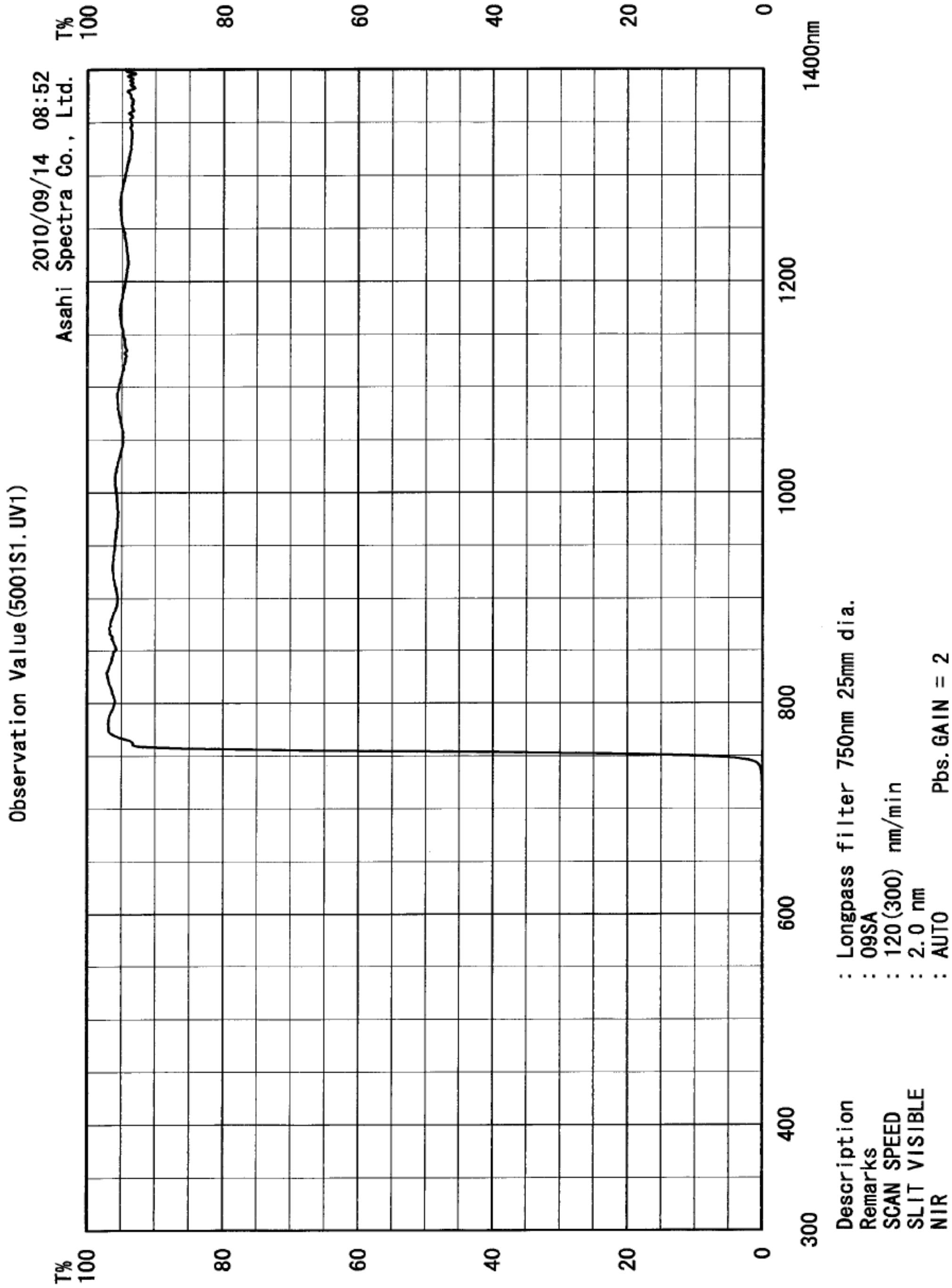
JOHN-B-25 filter



Shortpass filter



Longpass filter



Knife edges specifications

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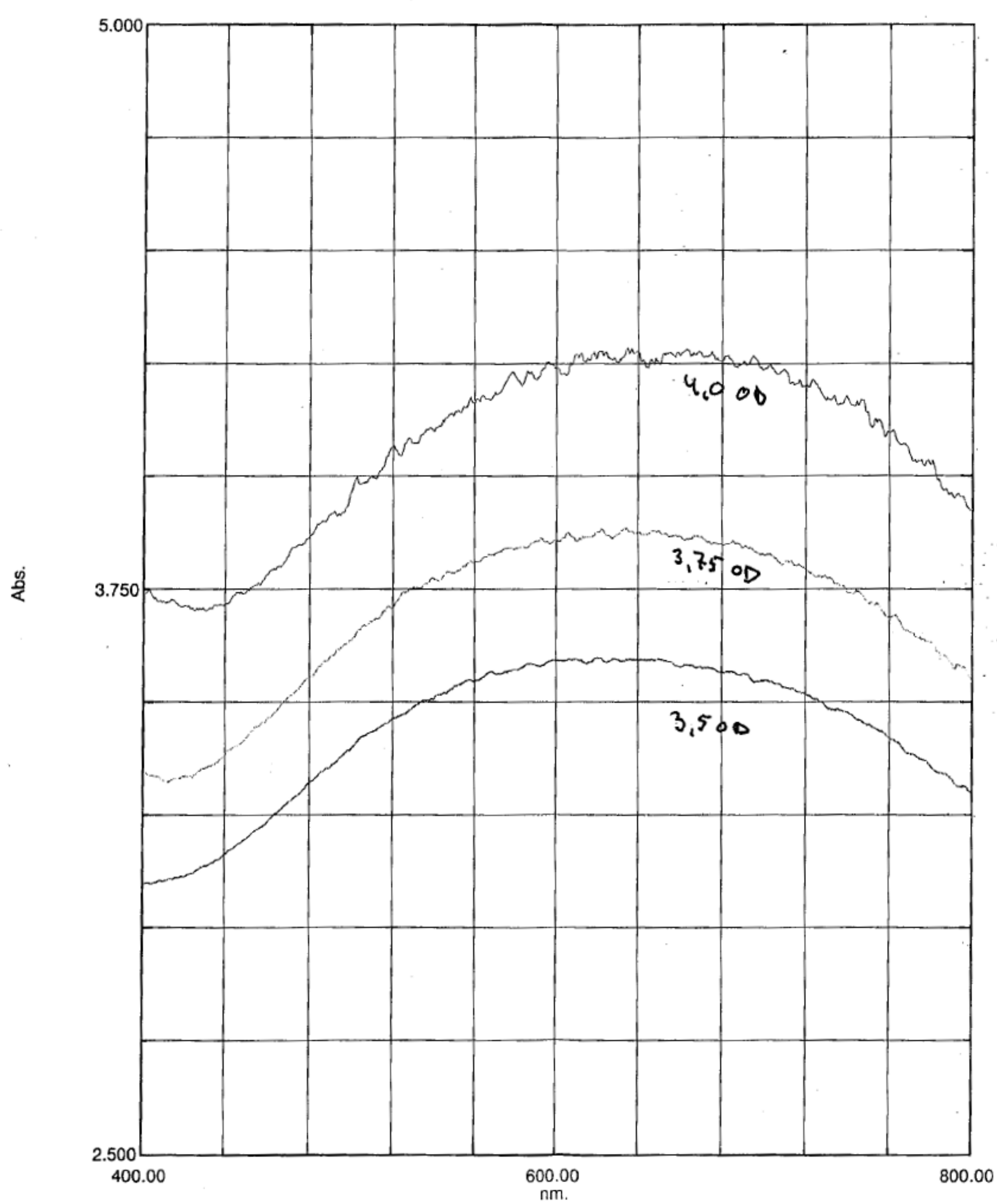
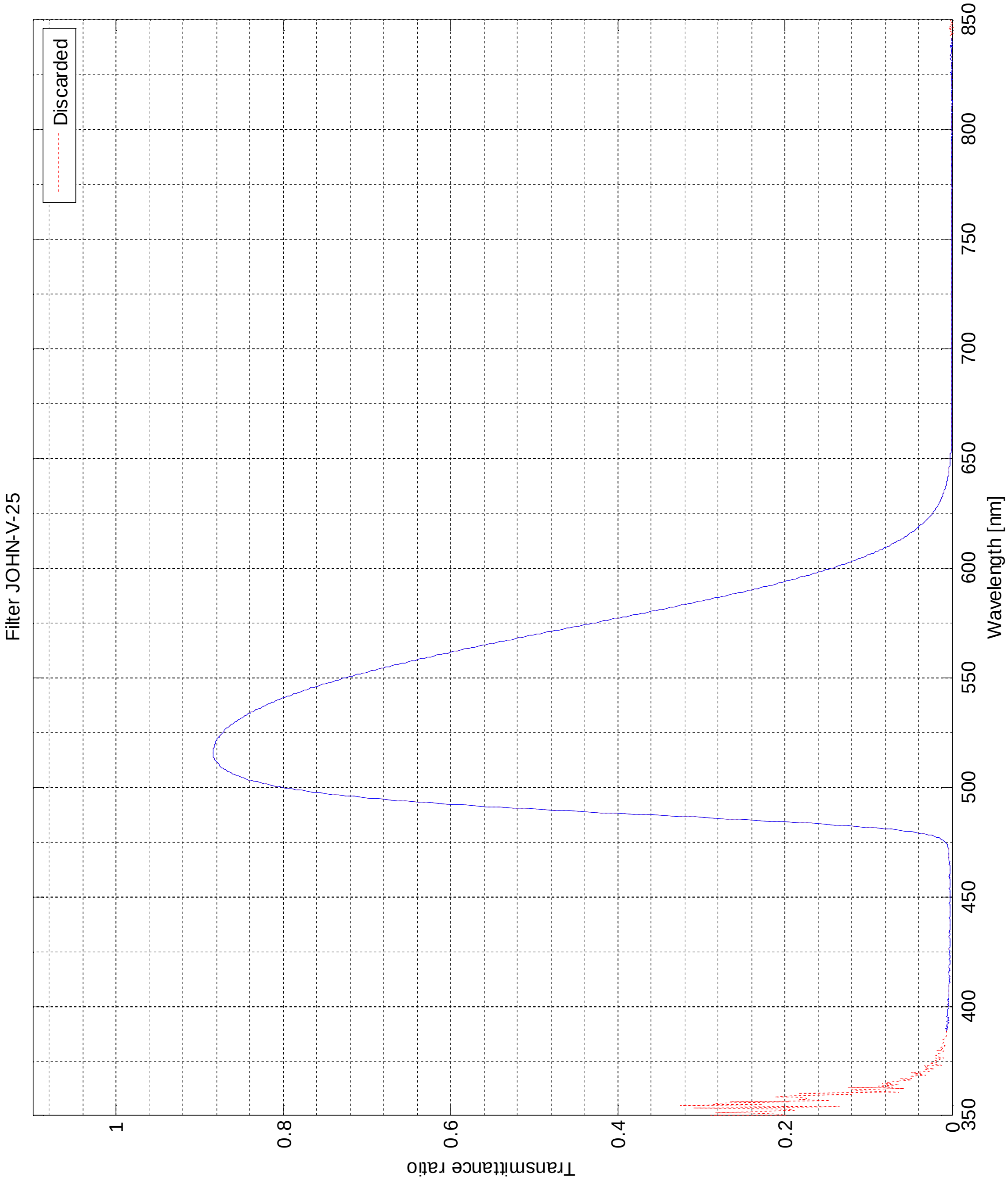
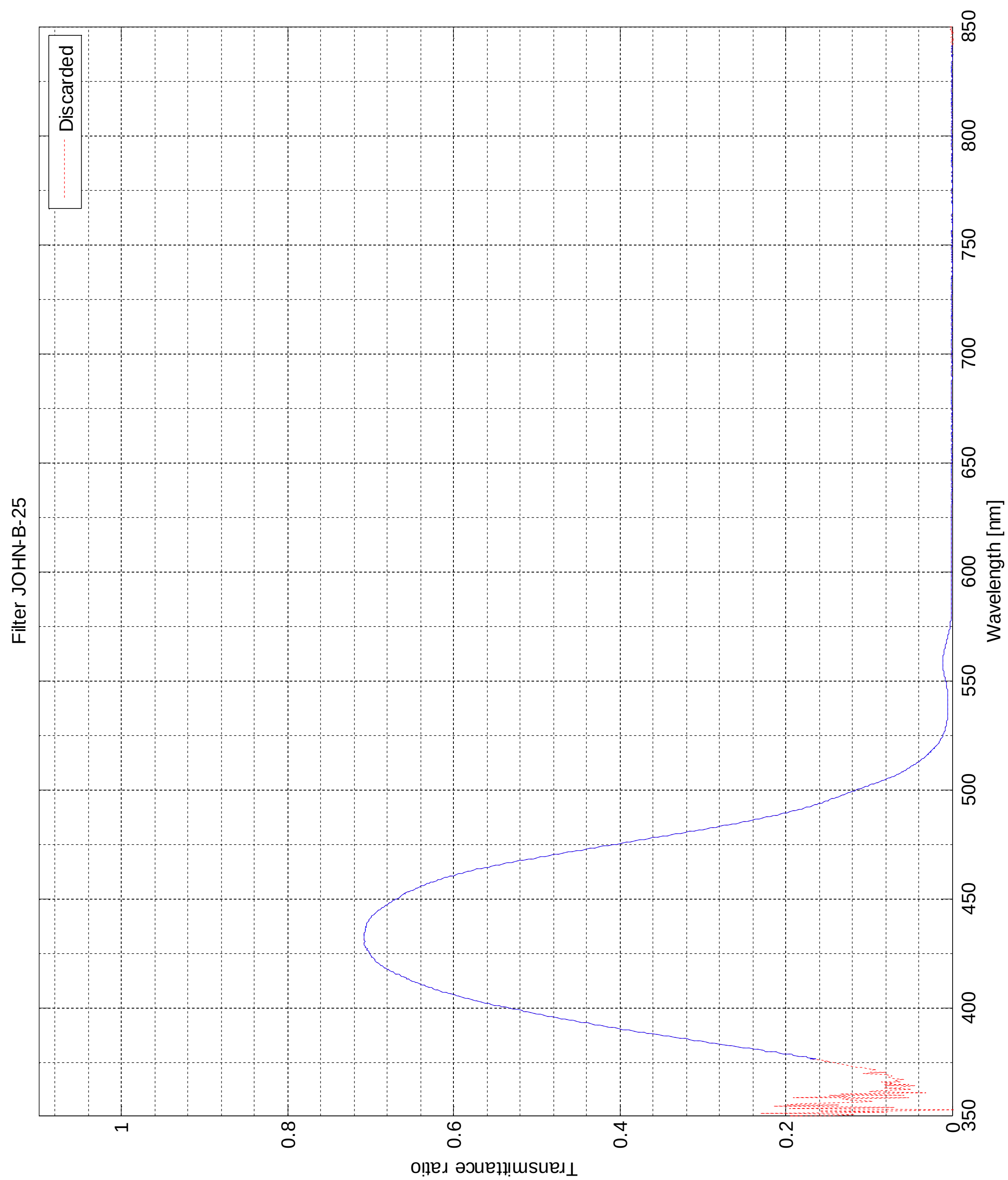


Appendix – Measured spectral transmittance

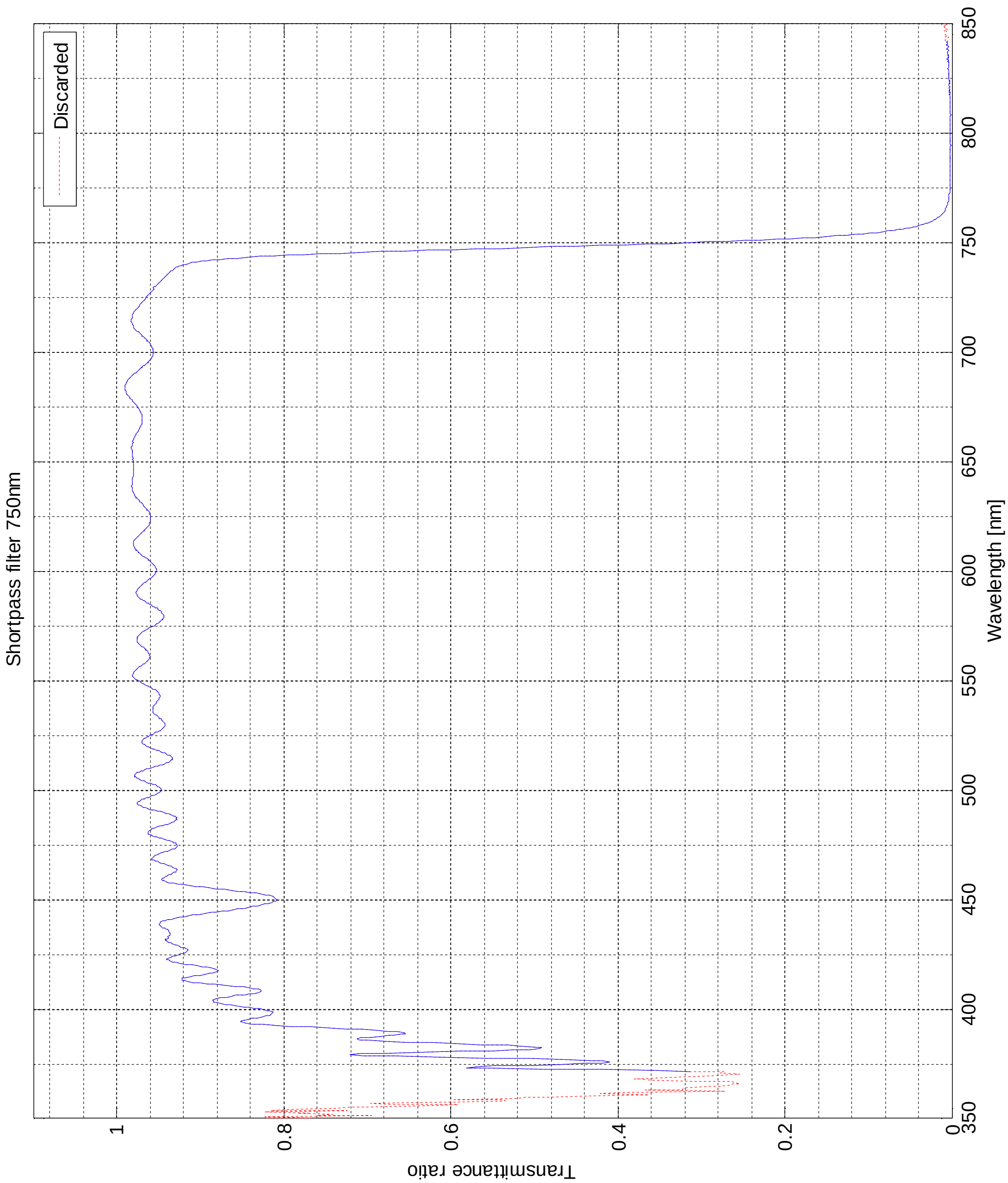
JOHN-V-25 filter



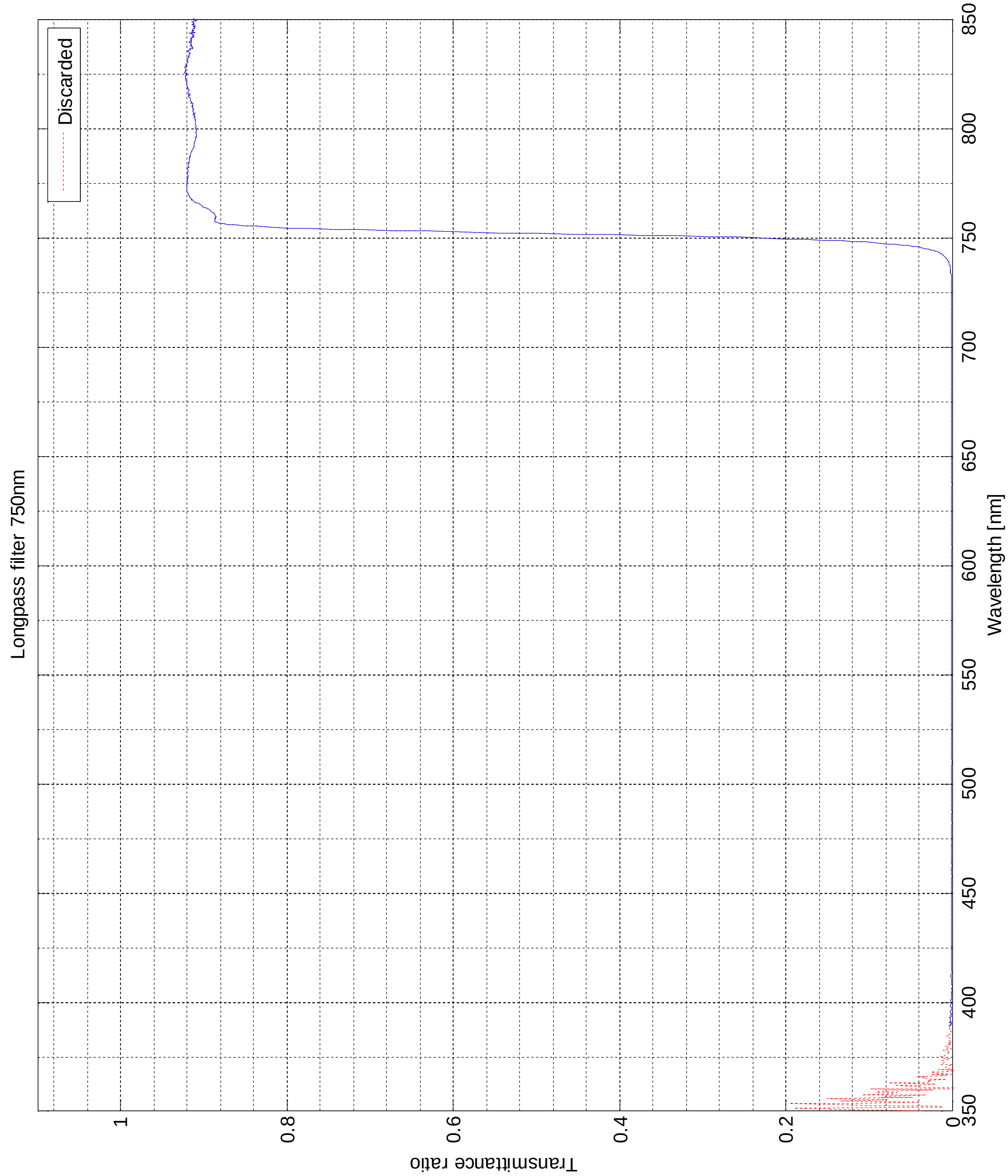
JOHN-B-25 filter



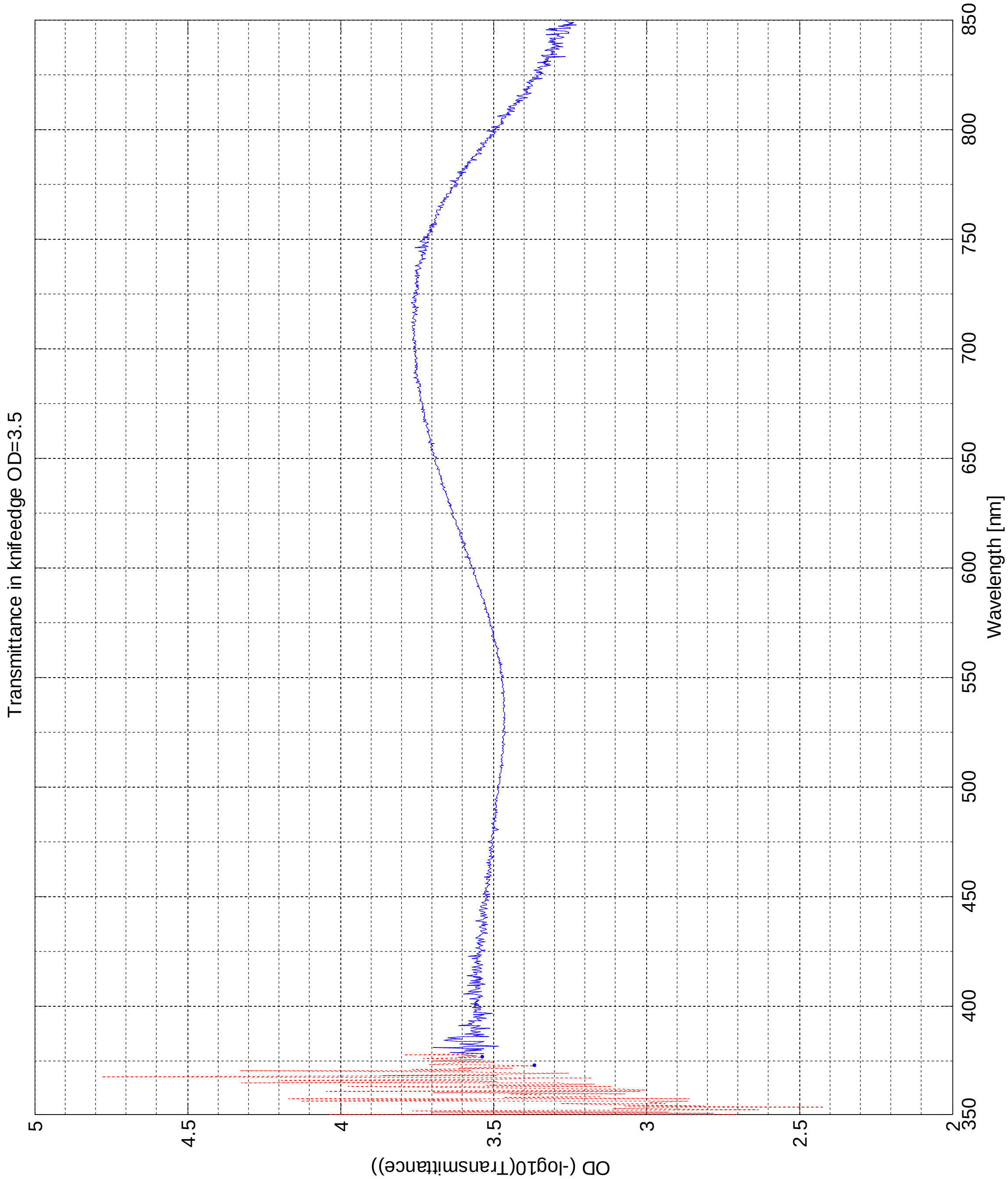
Shortpass filter



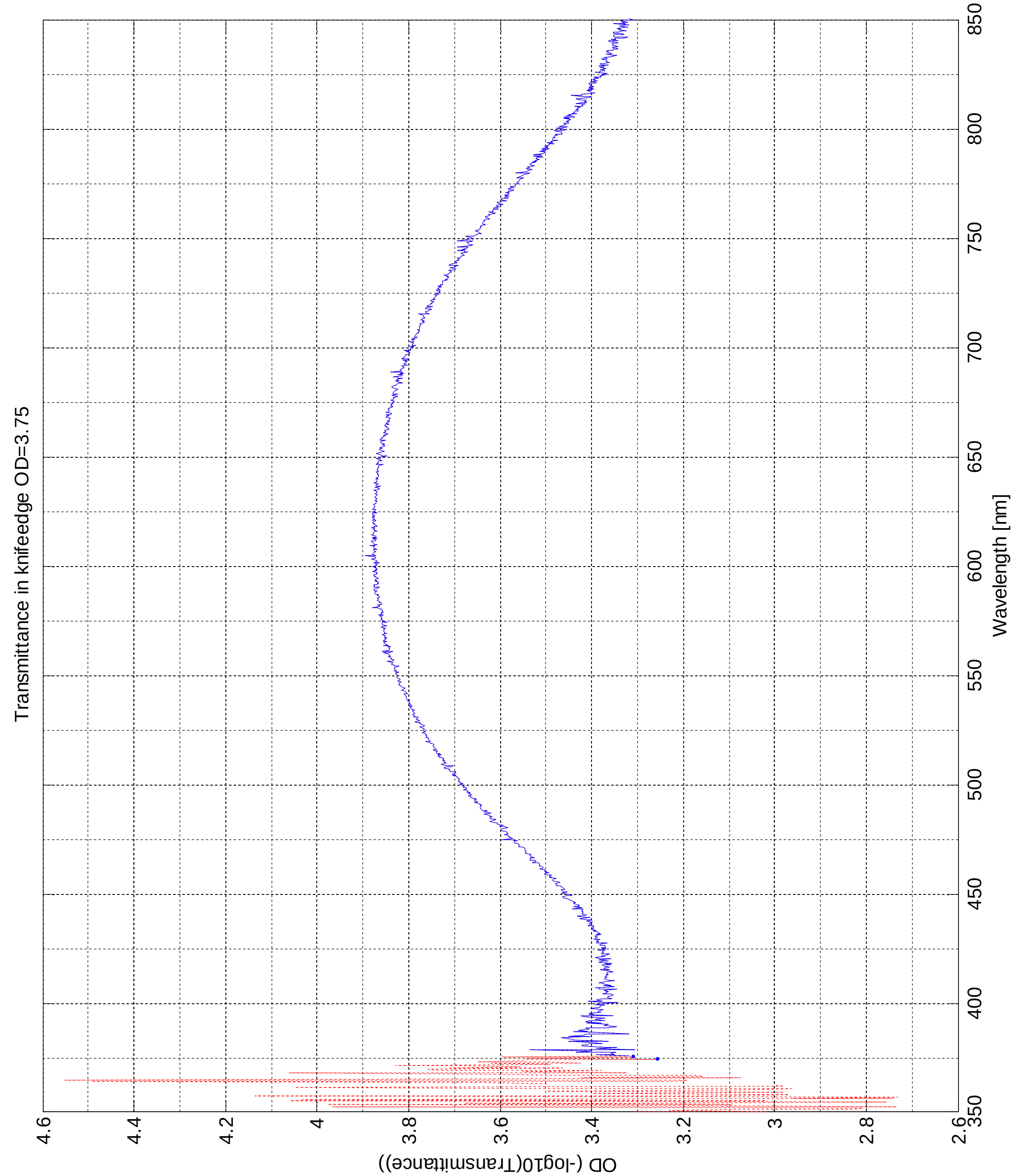
Longpass filter



Knife edge OD=3.5



Knife edge OD=3.75



Knife edge OD=4