Critical Design Review (CDR)
Of

ULTRA VIOLET IMAGING TELESCOPE (UVIT)

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CALIBRATION OF THE FM FILTERS FOR UVIT

UVIT-CDR-00-006

Indian Institute of Astrophysics
Bangalore-560034

Critical Design Review

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CALIBRATION OF THE FM FILTERS FOR UVIT

UVIT-CDR-00-006: V1.1

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CALIBRATION OF THE FM UVIT FILTERS: EXPERIMENTAL & ANALYSIS PROCEDURES ALONG WITH RESULTS

Introduction:

The Ultra Violet Imaging Telescope (UVIT) is one of the imaging payloads on-board the first Indian satellite devoted to Astronomy called ASTROSAT. The UVIT is intended to provide flux calibrated data at a high spatial resolution (about 1.5arcsec). It functions in three different spectral regions: (i) Far-Ultra Violet (FUV – 130nm to 180nm), (ii) Near Ultra Violet (NUV - 200nm to 300nm), and (iii) Visible (VIS - 320nm to 550nm). For each spectral region, a filter wheel is used for the designated filters. Table I, II, and III (FUV, NUV, and Visible respectively) below provides the final list of filters which would be available in the flight hardware along with its passband. Due to the unavailability of certain filters, some of the filter slots are not used in the final configuration compared with the projected one (Refer: ASTROSAT UVIT PDR Document March 2006).

In order to achieve the final intended flux calibrated high spatial resolution images, each optical components of UVIT needs to be calibrated. In this report, we provide the calibration experimental procedures and the analysis results for the Flight Model UVIT filters. Most of the procedures are similar to that carried out for the Engineering Model filter calibration (Refer: UVIT_Filter_Analysis_Cal Ver 0.5 dated: May 2010).

Table I - FUV Filter Wheel

Slot.No.	Filter Type	Filter Thickness	Passband	COMMENT
0	Block with Aluminium			
1	Calcium Fluoride - 1	2.50 mm	>125 nm	
2	Barium Fluoride	2.40 mm	>135 nm	
3	Sapphire Window	2.00 mm	>142 nm	
4	Grating - 1	4.48 mm		
5	Silica	2.70mm	> 159mm	
6	Grating – 2	4.48 mm		
7	Calcium Fluoride – 2	2.50mm	>125mm	

Table II - NUV Filter Wheel

Slot.No.	Filter Type	Filter Thickness	Passband	Material
0	Block with Aluminium			
1	Fused Silica Window	3.00 mm	> 159nm	
2	NUVB15	2.97 mm	200 nm – 230 nm	Silica (UV)
3	NUVB13	3.15 mm	230 nm – 260 nm	Silica (UV)
4	Grating	4.48 mm		
5	NUVB4	3.33 mm	250 nm – 280 nm	Silica (UV)
6	NUVN2	3.38 mm	275 nm – 285 nm	Silica (UV)
7	Fused Silica Window	3.30mm	> 159nm	

Table III - VISIBLE Filter Wheel

Slot.No.	Filter Type	Filter Thickness	Passband	Material
0	Block with Aluminium			
1	VIS 3	3.00 mm	400 nm – 530 nm	UBK 7
2	VIS 2	3.00 mm	370 nm – 410 nm	UBK 7
3	VIS 1	3.00 mm	320nm – 360 nm	UBK 7
4	Neutral Density Filter	3.00 mm		
5	BK7 Window	3.00mm		

The details of the experimental test procedures for filters are already discussed in the ASTROSAT – UVIT Optical Components Test Manual compiled by Abirami & Sriram. However, due to changes in the experimental test procedures for some of the experiments and to keep this as a complete document, the experimental procedures are explained very briefly.

Four filter parameters are to be derived from the ground calibrations, they are: (i) Spatial transmission variations, (ii) Transmission variation with wavelength, (iii) Focus shift, and (iv) Wedge angle. Software required for analysis for such experimental data was developed in IDL environment.

1. Spatial Transmission Variation:

Experiment:

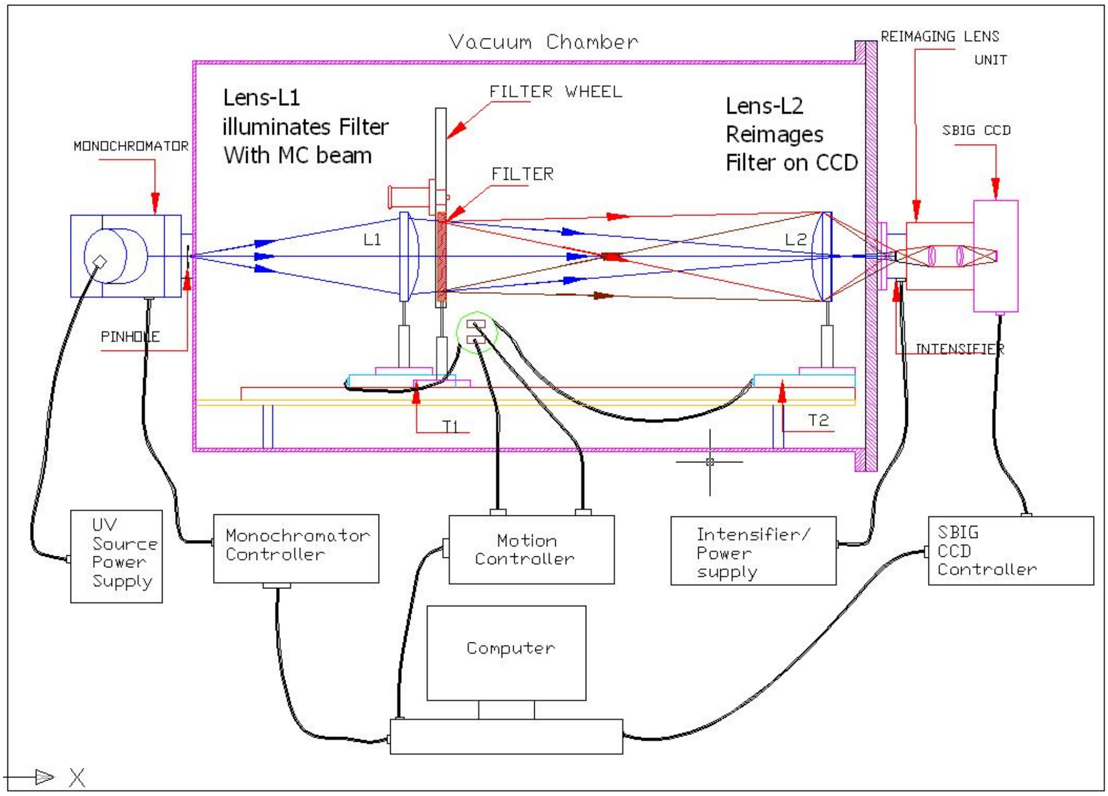


Figure 1: Experimental setup used for the spatial transmission variation

The experimental setup used for this experiment is given in Figure 1. Lens L1 is kept such a way that it produces a converging beam of the monochromator exit. The filter is kept at 50mm away from L1 so that the full filter is illuminated by this converging beam. Lens L2 images the filter on to an SBIG camera. Numbers of images are obtained with filter and without filter for central wavelength of the filter under study. Images are dark subtracted using the SBIG feature “dark also”. This is repeated for all the filters in FUV, NUV, and VIS filter wheel. Note that the lens L2 has to be moved in order to keep the filter at focus on the camera when wavelength is changed in the monochromator.

Analysis Steps Followed:

- First a circular Region-of-interest (ROI) is selected by the user. This is required as the image intensities are filled only a portion of the detector. The ROI selected is displayed in the window itself by the analysis software.
- Back ground subtraction is carried out by choosing a region away from the ROI. The region between 3- and 5-times the half-width of the ROI in the respective direction is

chosen and averaged to obtain the background counts.

- The quantity to be measured is the 2D intensity variation across the ROI when the filter is introduced.
- The measurements are done at a particular wavelength. This wavelength is chosen to be center wavelength of the corresponding filters.
- Five set of images are obtained for open as well as with filter. All the open images are averaged and the averaged image is then used to divide from each of the filter images.
- For pixels outside the ROI, the average value of the ratio within the ROI is replaced since the outside the ROI, the ratio is noisy (due to the low/no counts).
- A NXN pixel smoothening is done. This is to match the pixel scales of the CCD to that of the filter. This parameter is user selectable.
- A 2D display of the averaged image is displayed and saved.
- Due to the non-uniform nature of the source, the ratio does not remove all the source structures. Also, due to finite thickness and multiple reflection effects of filter, extra structures are visible in images with filters which were absent without filter. In order to take care of this effect, extra processing on the ratio obtained is carried out. The structures seen are either slit type or bright patches. Refer Appendix – G for the procedures used for removing these extra structures.

Outputs:

Two different types ("FITS" and "Postscipt") of outputs are created for each of the filter and stored in a directory called result. This directory resides inside the directory which contains the data. Apart from these files, there will be one "ASCII TXT" file listing different parameters of the experimental output. The details are given below:

- A "FITS" file for each of the filters in the filter wheel. The naming convention for this file is: "spatialvar_FILTERNAME_wavelength.fits" where FILTERNAME will be the name of the filter (e.g. MgF2 or Sapphire etc.) and wavelength is the wavelength for which this spatial variation file is obtained. We expect that these "FITS" files are the final files used by the calibration procedures. The fits file will have the full header and a table containing the experiment specific information.
- A table of spatial transmission is also provided in this fits result. This table is of 512 X 512 in size.
- This file also has an extension fits header and a table providing the average spatial transmission for this particular wavelength by averaging the ROI selected during the analysis process.
- A single ASCII file containing the necessary header information as well as the derived average spatial variation is generated in the following format: First the full header and then the derived values as a result. The name of this file will be ``result_spatialvar_overall.txt''. This is generated in order to create the wavelength transmission profiles (refer wavelength transmission section in this report).
- A postscript file of the spatial transmission variation is also created for the particular wavelength of interest (Figure 2 for an example).
- An image of the mask is also taken for reference. This would be used to identify the

relative orientation of the filters with respect to the detectors. This is required since all the spatial variation experiments is carried out with a SBIG camera which is very different from the final camera used in the final flight hardware (Figure 3).

- Appendix – A shows the average spatial variation results for all the filters (FUV, NUV, and VIS) as tables after removing the source structures using the methodology mentioned in Appendix-G.

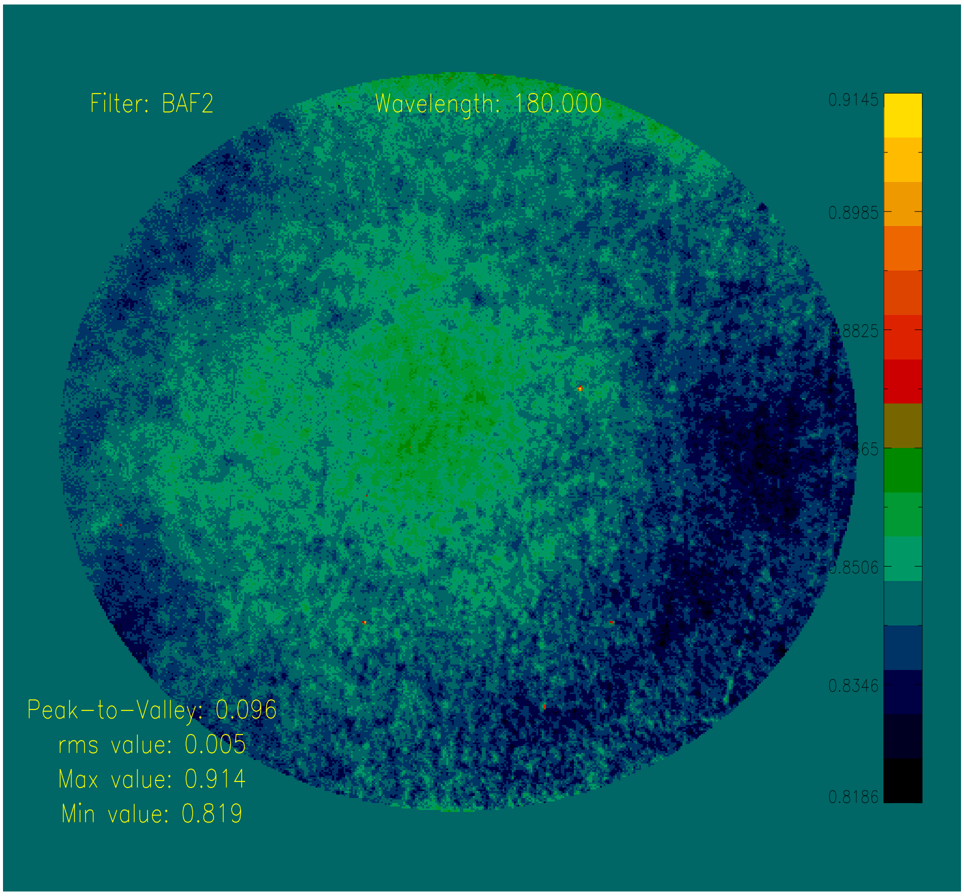


Figure 2: Postscript file showing the spatial transmission variation for the BaF2 filter at 180.0nm. The peak-to-valley, rms value, max. and min. value within the ROI is listed in this figure. Color bar on the right shows the variation of the spatial transmission.

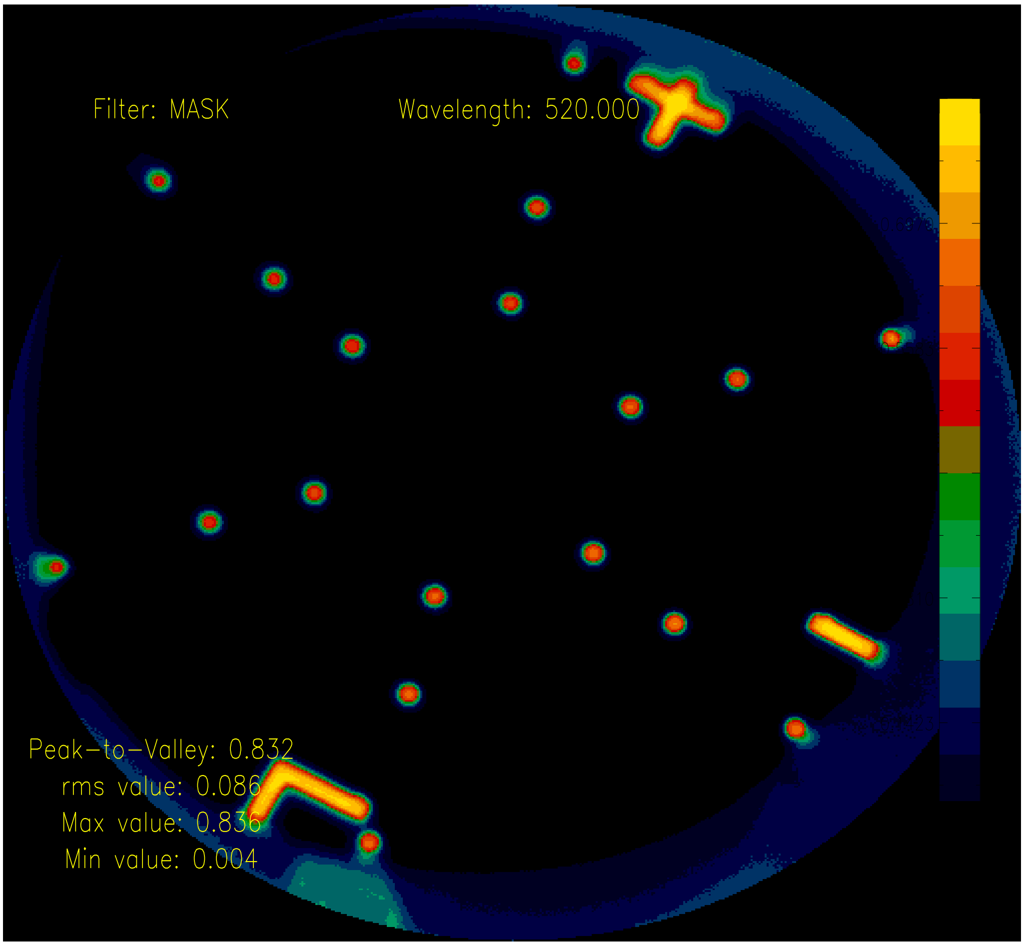


Figure 3: Image of the reference mask placed in the visible filter wheel. Such reference mask image will be taken after FM integration along with the FM detector. This would be used for getting the correct orientation and scaling of the filter spatial variation which will be used in the post processing of UVIT data.

2. Wavelength Transmission:

Experiment:

- Experiment is similar to that of spatial variation. In other words, spatial variation experiment is repeated for several different wavelengths to obtain the required data for the wavelength transmission. Please refer to spatial variation experiment.

Analysis Steps Followed:

- Analysis procedures are similar to that of the spatial variation.
- The average value for the ROI is obtained for different input wavelengths and that provides the required parameter.

Outputs:

Three different types ("FITS", "Postscipt", and "ASCII TEXT") of outputs are created for each of the filter and stored in a directory called result. This directory resides inside the directory which contains the data. Apart from these files, there will be one "Postscript" file providing plots for all the filters as a single plot and one "ASCII TXT" file listing different parameters of the experimental output. The details are given below:

- A "FITS" file for each of the filters in the filter wheel. The naming convention for this file is: "spetrans_FILTERNAME_avg.fits" where FILTERNAME will be the name of the filter (e.g. MgF2 or Sapphire etc.). We expect that these "FITS" files are the final files used by the calibration procedures. The fits file will have the full header and a table containing the experiment specific information.
- An extended header along with the table containing the average transmission (along with its error) is also stored.
- There will be one "Postscript" file for each filter containing the wavelength transmission.
- The results for all the FM filters (FUV, NUV, and Visible) are provided in Appendix-B

3. Focus Shift:

Experiment:

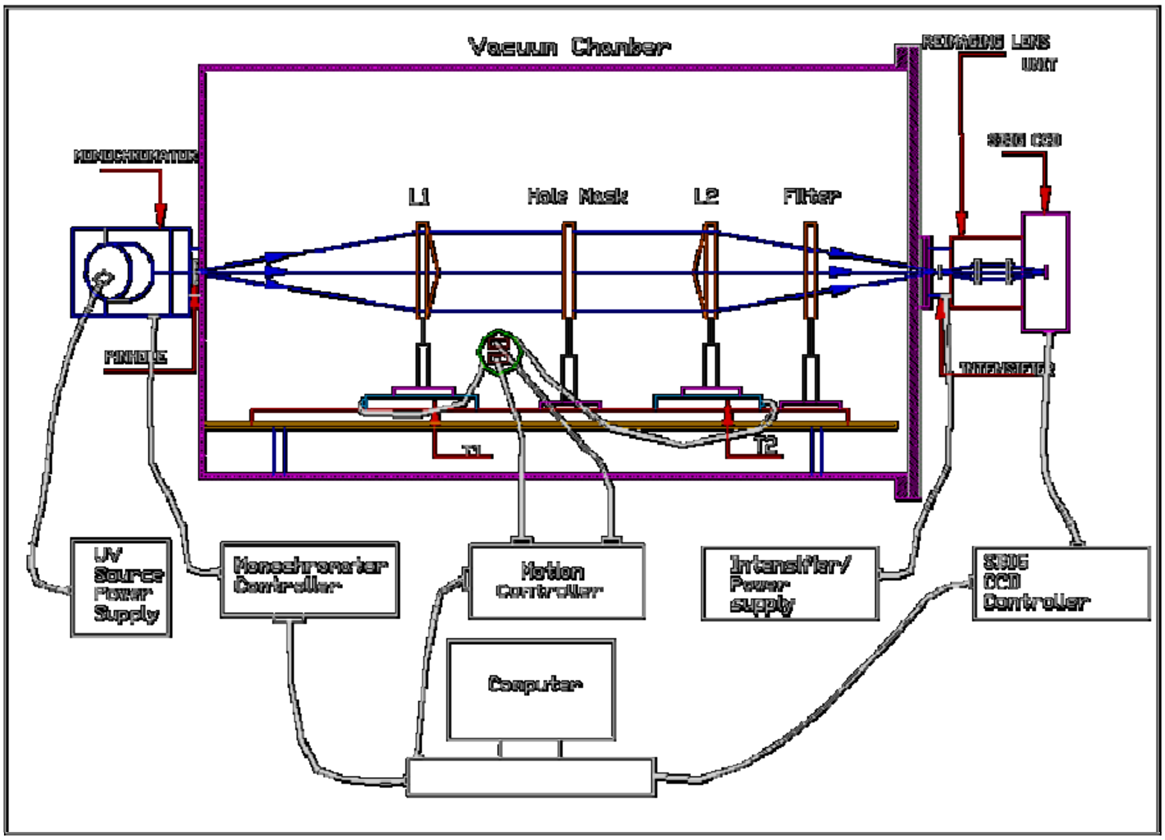


Figure 4: Experimental setup used for the Spatial transmission variation

- A Hartmann mask (two pinholes) is imaged with the filter first. The camera is placed away from the focus in order to have the two mask images separated by about 30-pixels on the SBIG camera (pixel size 20microns).
- The filter is placed in the converging beam after the second (imaging) lens.
- Once the Hartmann mask is imaged with the filter, the filter is removed from the beam.
- Hartmann Mask images are taken by moving the imaging lens to 2mm in steps of 0.5mm. The direction of motion should be towards the filter wheel and the separation decreases with lens motion. (NOTE: Without the filter the separation will be larger since taking out the filter moves the focus towards the imaging lens).
- For each 0.5mm position of the imaging lens N-number of images are obtained (For FM N=10).
- The separation of the Hartmann images (pinhole images) provides us information about the focus shift.
- Obtained images are dark subtracted while obtaining the data itself.
- Central wavelength for each filters are used for this experiment.

Analysis Steps Followed:

- Cosmic ray pixel removal is carried out by finding out the pixels and replace that pixel intensity with the nearby average pixel values (Appendix-E provides the details for this particular step).
- Back ground subtraction is carried out by choosing a region away from the pin-hole image. Regions between 5- and 10-times the SIGMA of the pin-hole image is chosen for the background estimation (Appendix-F provides the details of this particular step).
- A 2D and two Gaussian function fit is carried out to find the maximum positions [(x_1,y_1) and (x_2,y_2)] as well as the SIGMAS of each of the 2D Gaussians.
- The difference between these two maximum positions ($\text{sqrt}((x_2-x_1)^2+(y_2-y_1)^2)$) is then calculated.
- This is repeated for all positions of the L2 without the filter.
- A plot of the calculated separation versus the movement of the imaging lens for the data **without filter** is then fitted with a straight line equation.
- The differences obtained for data with filters are taken as the reference for different filters.
- The straight line fit will provide us with the slope and the constant term for the data without the filter. By equating the straight line equation to that of the reference value (obtained with the filter) and solving for the value of 'x (or the L2 position)' will give the focus shift due to the filter. The error in the straight line fit will provide the error in the focus shift measurement (through error propagation).

Outputs:

One "FITS" file is created for each filter and stored in a directory called result. This directory resides inside the directory which contains the data. Apart from these fits files, there is one "ASCII TEXT" file for each filter providing different parameters of the experimental output. The details are given below:

- "FITS" file containing the results as a table. The name of this file is: "focushft_FILTNAME_WLEN.fits". We expect that this "FITS" file is the final file used by the calibration procedures. The fits file will have the full header and a table containing the experiment specific information. FILTNAME corresponds to the specific filter name and WLEN corresponds to the wavelength at which this is obtained.
- There will be several "Postscript" files containing the plot of the lens position versus the separation of the Hartmann mask images. Each filter will have a corresponding ``ps'' file. The naming convention for this file is: ``focushft_FILTERNAME_WLEN.ps'' where FILTERNAME will be the name of the filter (e.g. MgF2 or Sapphire etc.) and WLEN corresponds to the wavelength for which the filter shift is derived. These ``postscript'' file are generated only for convenience of looking at the results.
- For all the filters (FUV, NUV, and Visible) the focus shift results are provided in the Appendix - C

4. Wedge Angle Measurement:

Experiment:

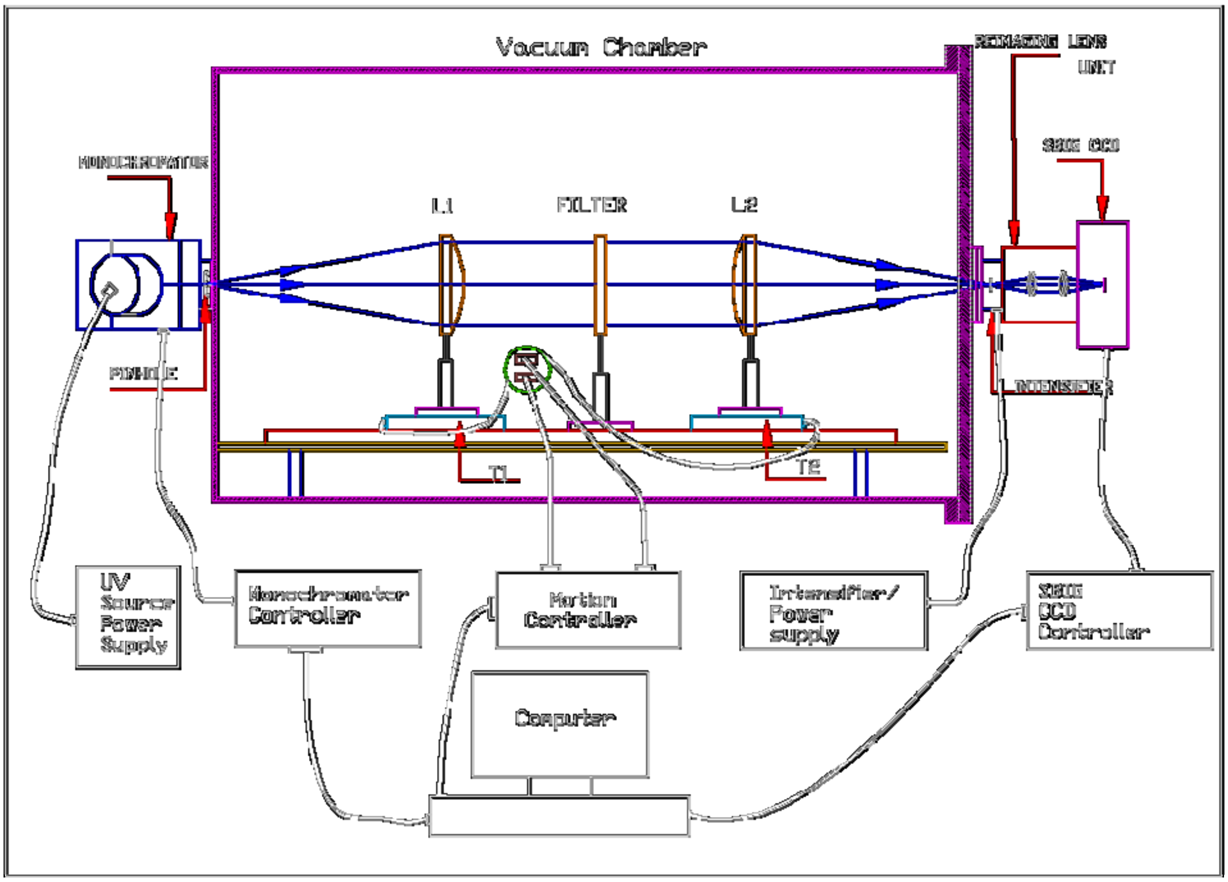


Figure 5: Experimental setup for the Wedge angle measurement.

- A pinhole (diameter of 100micron) is imaged with and without filter.
- Filter is placed in the collimated beam.
- N-number (for FM N=10) set of pin-hole images with and without filter for a set of wavelength depending on the filter under study.
- The dark image of the CCD was subtracted while obtaining the data.
- Same data set obtained for the Filter wavelength transmission can be used.

Analysis Steps Followed:

- Cosmic ray pixel removal is carried out by finding out the pixels and replace that pixel intensity with the nearby average pixel values (Appendix-E provides the details for this particular step).
- Back ground subtraction is carried out by choosing a region away from the pin-hole image. Regions between 5- and 10-times the SIGMA of the pin-hole image is chosen for

the background estimation (Appendix-F provides the details of this particular step).

- A 2D Gaussian fit is carried out to find the maximum position as well as the SIGMAS of the 2D Gaussians.
- Centroid algorithm is used to find the accurate centroid position of the pin-hole image.
- N-number (For FM N = 10) set of observation is carried out for each filter and for a set of wavelength.
- Centroid is found out for the N- sets of images with filter as well as for the open images.
- The differential shift between the centroids with filter and with the open image is the shift due to the filter.
- The shift in pixels is multiplied by the pixel size (20micron for the SBIG used) and then divided by the focal length of the lens. The result is nothing but the tangent of the angular deviation of the beam due to the wedge angle of the filter. Inverse tangent of this value provides the wedge angle.
- The average wedge angle value (from the N-set of measurement for a particular filter and a particular wavelength) is taken as the mean and the standard deviation as the error in the wedge angle calculations.
- The above procedure is repeated for all the filters available in the filter wheel.

Outputs:

Only "FITS" files are created for each of the filter and for each wavelength and stored in a directory called result. This directory resides inside the directory which contains the data. The details are given below:

- A "FITS" file for each of the filters in the filter wheel. The naming convention for this file is: "wedgeang_FILTERNAME_WLEN_avg.fits" where FILTERNAME will be the name of the filter (e.g. MgF2 or Sapphire etc.) and WLEN is the wavelength of observation (e.g. 130.00nm etc.). We expect that these "FITS" files are the final files used for the final calibration database. The fits file will have the full header and a table containing the experiment specific information.
- A single ASCII file for containing the necessary header information as well as the derived wedge angle value will also be available.
- Appendix-D provides the result for all the filters (FUV, NUV, and Visible).

General Remarks:

- The filter slot number assigned for the calibration experiments are different from that of the final filter slot numbers. However, the order of filters in the filter wheel is arranged in the same order as shown in the Table (I), (II), and (III). Hence, this requires only a change in the header files of the calibration results before this can be used in the calibration data base.

Appendix A: Spatial Variation Results

FUV – Results:

Below Table shows the results for all the FM-FUV filters at the wavelength of interests.

Filter Slot No.	Filter Name	Wavelength (nm)	Exp. Time (Sec)	PTV	Max.	Min.	(Max.–Min.)* 100/Max	Requirement (Uniformity)	Remarks
4	CaF2-1	156.0	1.0	0.037	0.778	0.740	4.78%	< ± 10%	Complied
3	BaF2	158.0	0.5	0.059	0.768	0.709	7.71%	< ± 10%	Complied
2	Sapphire	160.0	1.0	0.055	0.730	0.675	7.55%	< ± 10%	Complied
6	CaF2-2	156.0	1.0	0.076	0.790	0.714	9.69%	< ± 10%	Complied
0	Silica	170.0	3.0	0.045	0.710	0.664	6.34%	< ± 10%	Complied

***If one excludes the local spots, which cover < 1% area and are < 1 mm (as compared to > 3 mm diameter of the beam at the filter), all the variations are within +-3% of the mean transmission.**

NUV – Results:

Below table shows the results for all the FM-NUV filters at the wavelength of interests.

Filter Slot No.	Filter Name	Wavelength (nm)	Exp. Time (Sec)	PTV	Max.	Min.	(Max.–Min.)* 100/Max	Requirement (Uniformity)	Remarks
6	Silica3.0	300.0	2.0	0.067	0.951	0.884	7.05%	< ± 10%	Complied
7	NUVB15	214.0	2.0	0.174	0.190	0.016	91.58%	< ± 10%	Refer (1)
0	NUVB13	244.0	2.0	0.070	0.733	0.663	9.55%	< ± 10%	Complied
2	NUVB4	264.0	2.0	0.060	0.742	0.682	8.09%	< ± 10%	Complied
3	NUVN2	280.0	2.0	0.096	0.744	0.647	12.90%	< ± 10%	Refer (2)
4	Silica3.3	300.0	2.0	0.059	0.947	0.888	6.23%	< ± 10%	Complied

(1) Large deviation, measurement with different setup is carried out for this filter alone.
(2) Dark spots at two places in the edge of the filter. Dust particle?
***If one excludes the local spots, which cover < 1% area and are < 1 mm (as compared to > 3 mm diameter of the beam at the filter), all the variations are within +-3% of the mean transmission, except for the filter NUVB15.**

Visible – Results:

Below table shows the results for all the FM-Visible filters at the wavelength of interests.

Filter Slot No.	Filter Name	Wavelength (nm)	Exp. Time (Sec)	PTV	Max.	Min.	(Max.–Min.)* 100/Max	Requirement (Uniformity)	Remarks
3	VIS1	340.0	0.75	0.067	0.747	0.680	8.97%	< ± 10%	Complied
2	VIS2	390.0	1.0	0.081	0.875	0.794	9.26%	< ± 10%	Complied
1	VIS3	470.0	3.0	0.100	0.994	0.894	10.06%	< ± 10%	Refer (3)
5	BK7	420.0	1.5	0.049	0.941	0.893	5.21%	< ± 10%	Complied

4	NDF	420.0	1.5	0.175	1.000	0.825	17.50%	< ± 10%	Refer (4)

(3) Dark spot at one place in the filter. Dust Particle?

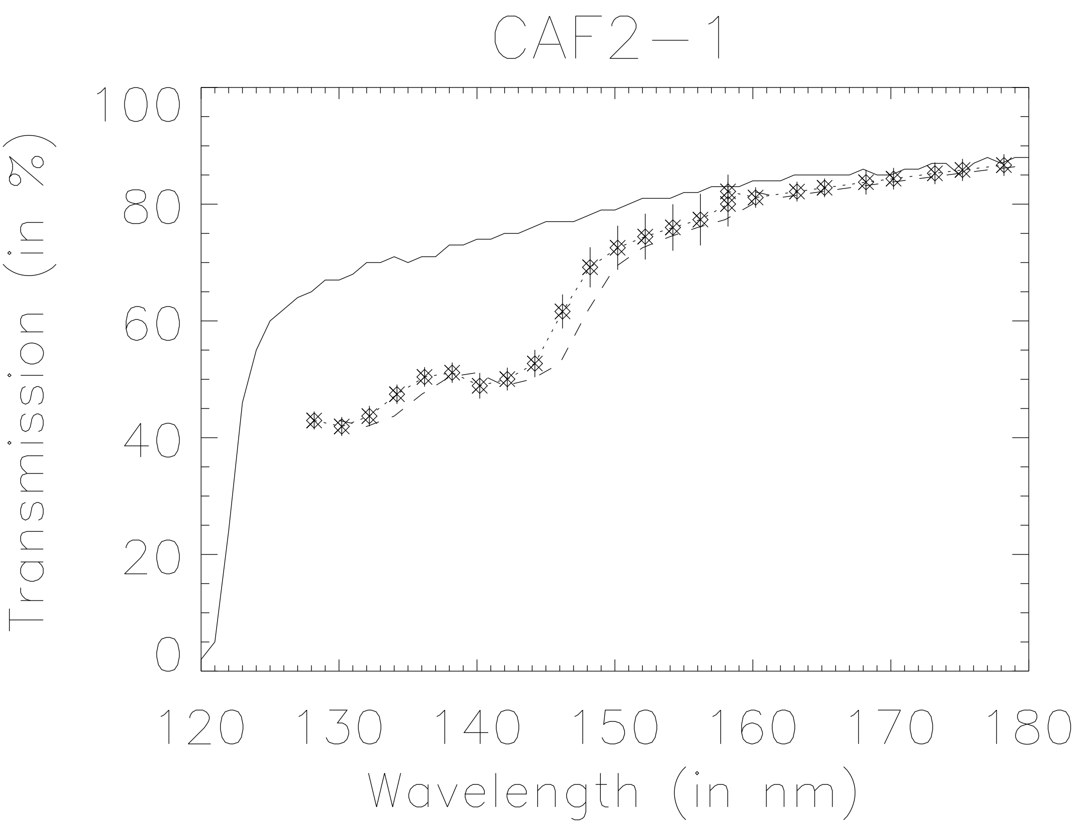
(4) There is a new NDF filter which will replace this one as the transmission of this NDF is very high.

***If one excludes the local spots, which cover < 1% area and are < 1 mm (as compared to > 3 mm diameter of the beam at the filter), all the variations are within +-3% of the mean transmission.**

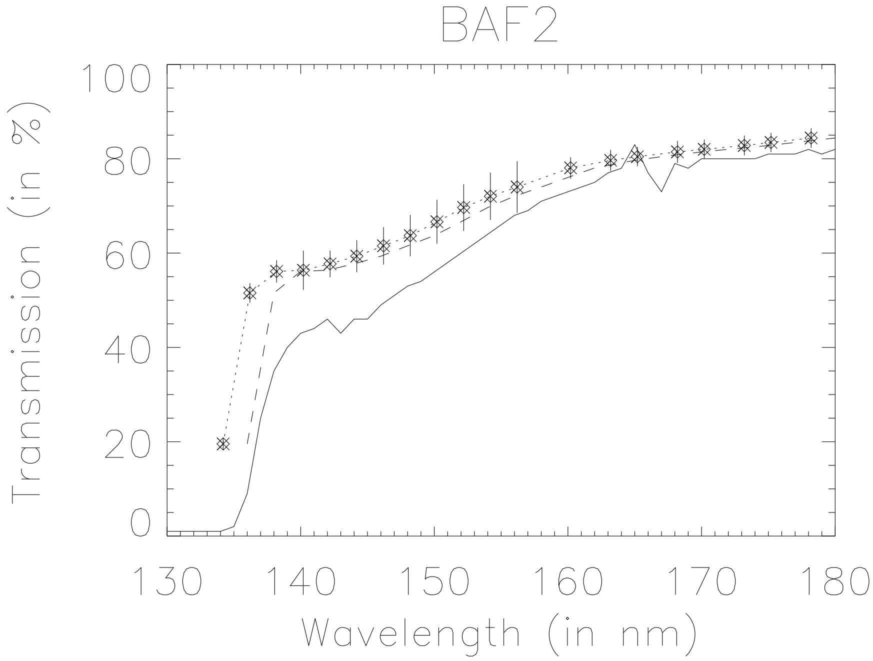
Appendix B: Wavelength Transmission Results

FUV – Results:

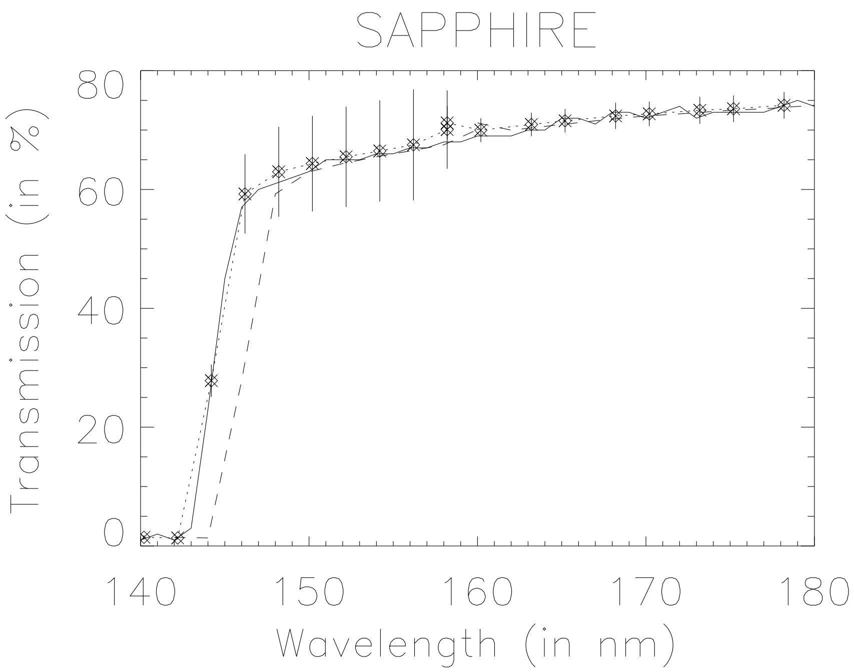
Below figures shows the results for all the FM-FUV filters. Points with error bars are the measured ones where as the solid line are the literature values. A wavelength offset of -1.8nm has to be added to the experimental values to match with the literature curve. This offset value was estimated from the Sapphire and Silica transmission curve. This constant value is applied to all the filters since the optical setup is same for all of the filter transmission measurement in FUV. All measurements were carried out at the MGKM Laboratory.



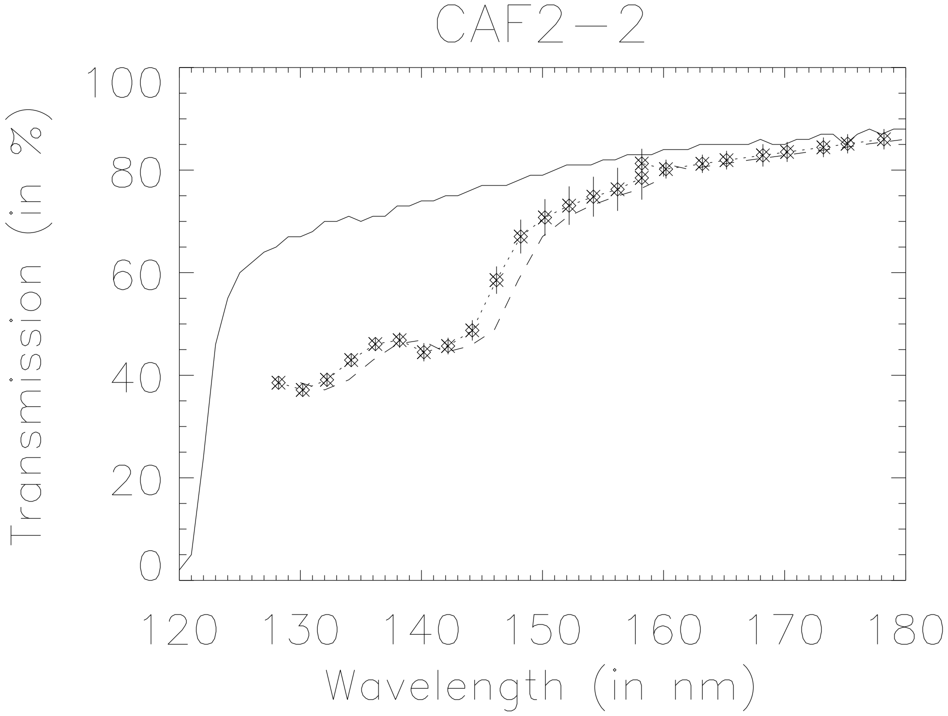
Transmission curve for CaF2-1 filter. Solid line: Literature curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -1.8nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -1.8nm wavelength shift for comparison.



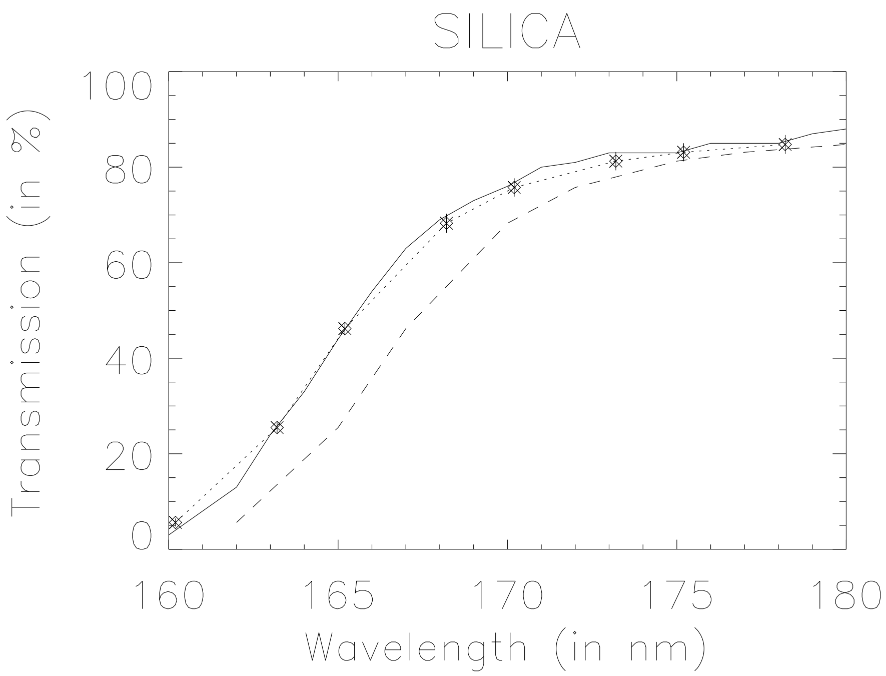
Transmission curve for BaF2 filter. Solid line: Literature curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -1.8nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -1.8nm wavelength shift for comparison.



Transmission curve for Sapphire filter. Solid line: Literature curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -1.8nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -1.8nm wavelength shift for comparison.



Transmission curve for CaF2-2 filter. Solid line: Literature curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -1.8nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -1.8nm wavelength shift for comparison.

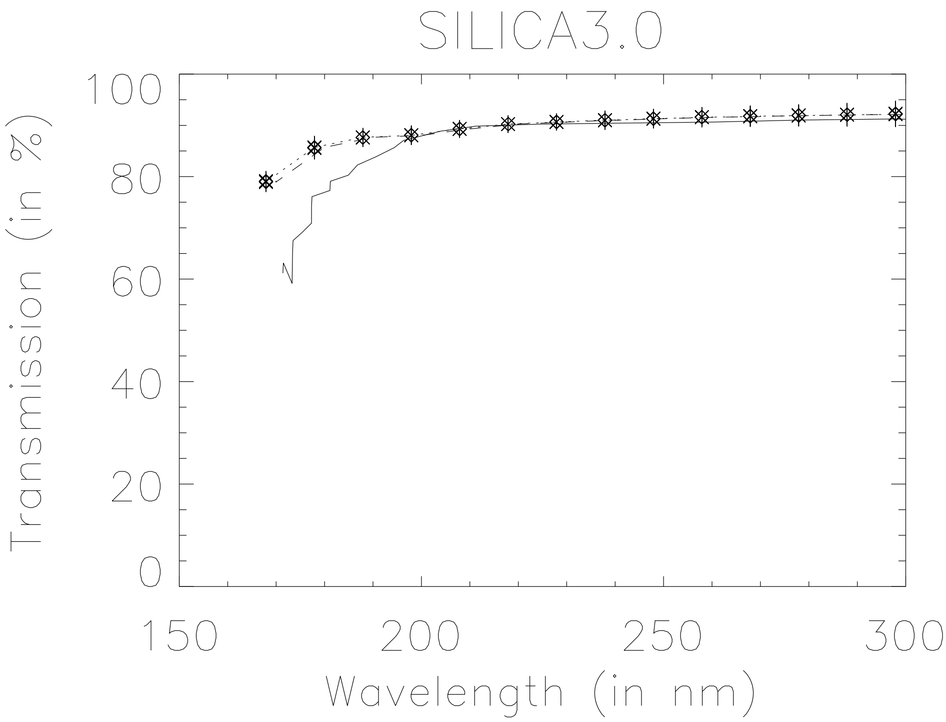


Transmission curve for Silica filter. Solid line: Literature curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -1.8nm (as explained in the text). Error bars are 3-times the measurement error.

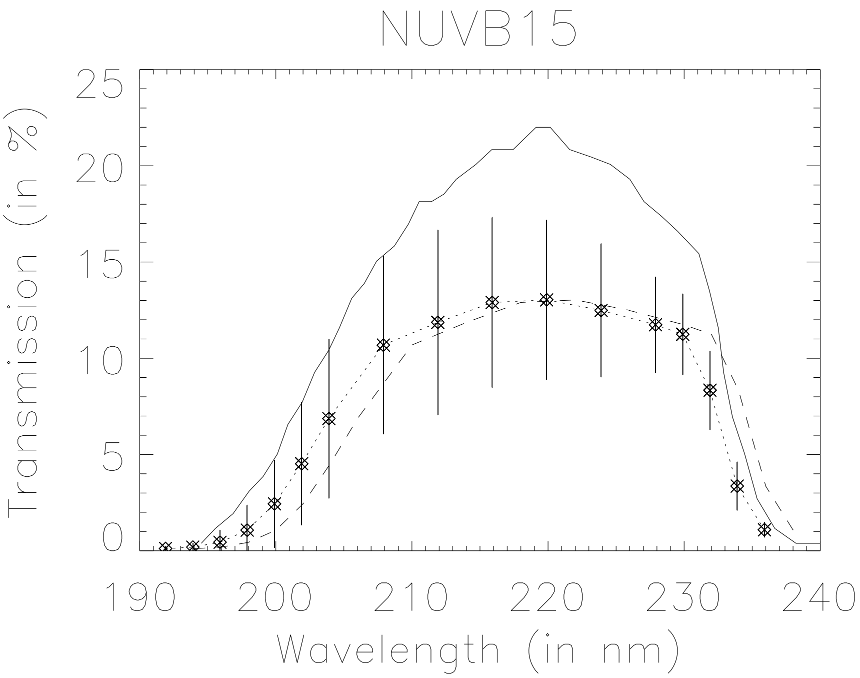
Dashed line: Actual measurement without the -1.8nm wavelength shift for comparison.

NUV – Results:

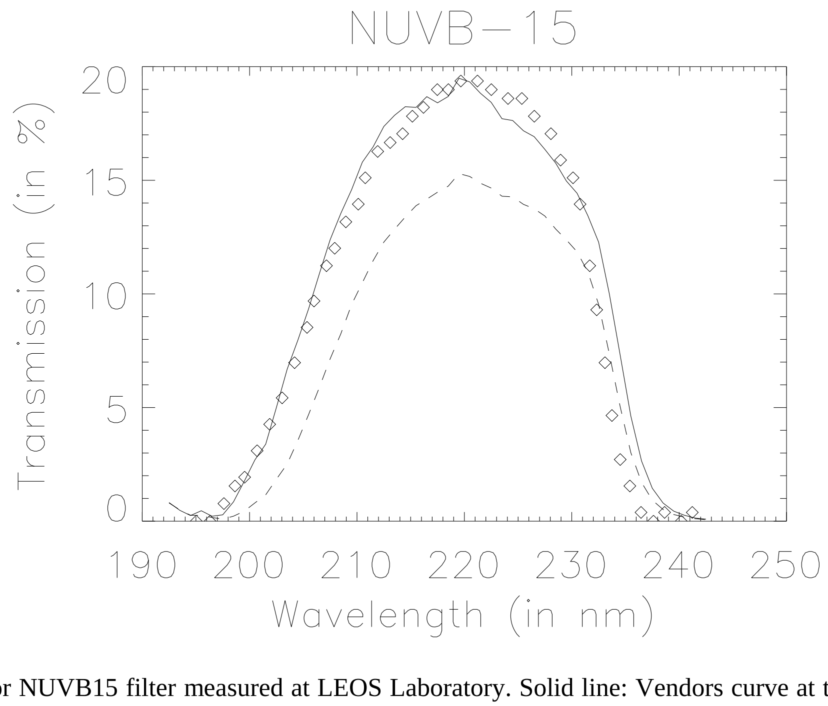
Below figures shows the results for all the FM-NUV filters. Points with error bars are the measured ones where as the solid line are the vendor values for narrow band filters and literature value for the broadband filters. A wavelength offset of -2.1nm has to be added to the experimental values to match with the vendors curve. This offset value was estimated from the NUVN2 filter which has the narrowest band. This constant offset is applied to all the filters since the optical setup is same for all of the filter transmission measurement in NUV. All the measurements were carried out at the MGKM laboratory except for the NUVB15 where extra measurements are done at LEOS and marked in the respective figure captions.



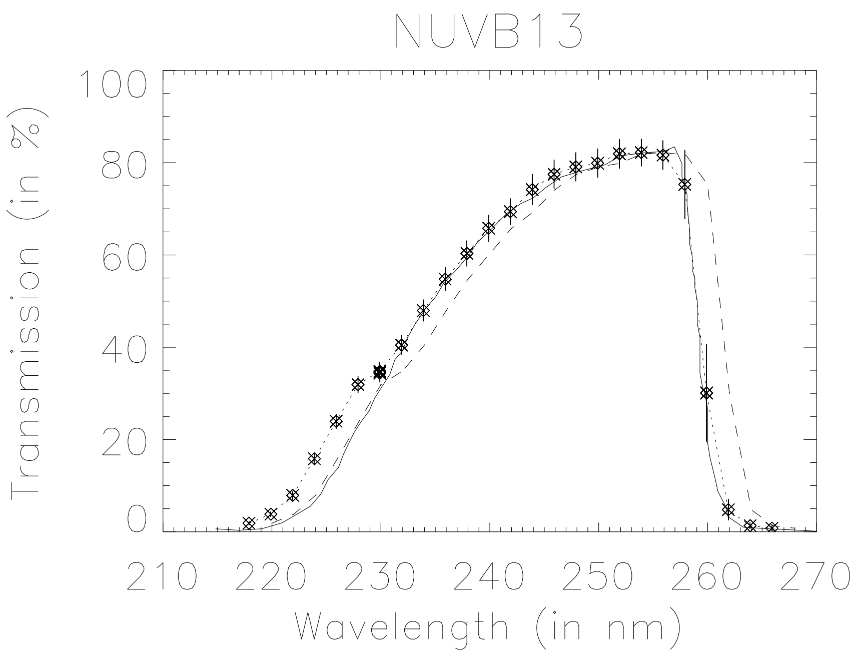
Transmission curve for Silica 3.0mm thickness filter. Solid line: Literature curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -2.1nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -2.1nm wavelength shift for comparison.



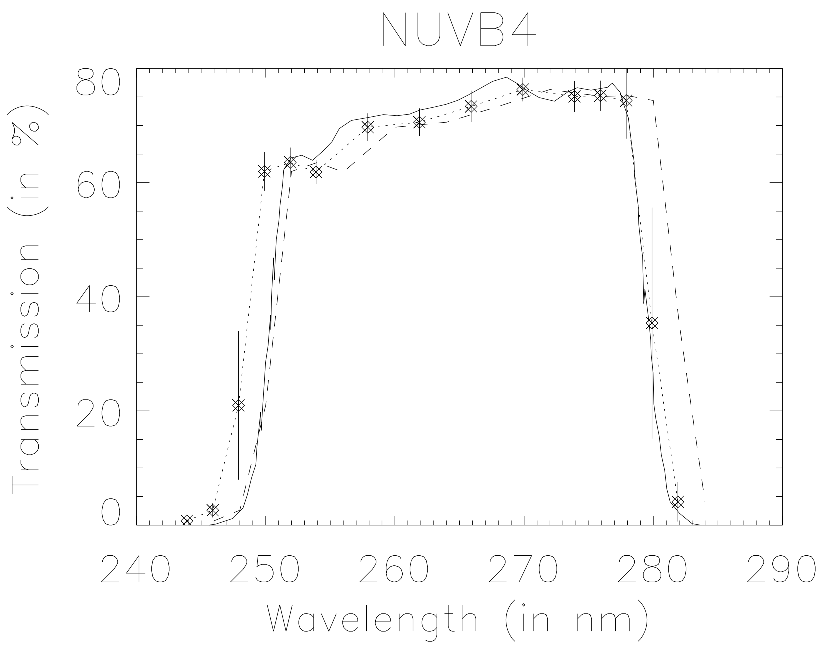
Transmission curve for NUVB15 filter measured at MGKM Laboratory. Solid line: Vendors curve at the centre of the filter. Data Points connected by dotted line: Measurement with the wavelength shifted by -2.1nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -2.1nm wavelength shift for comparison.



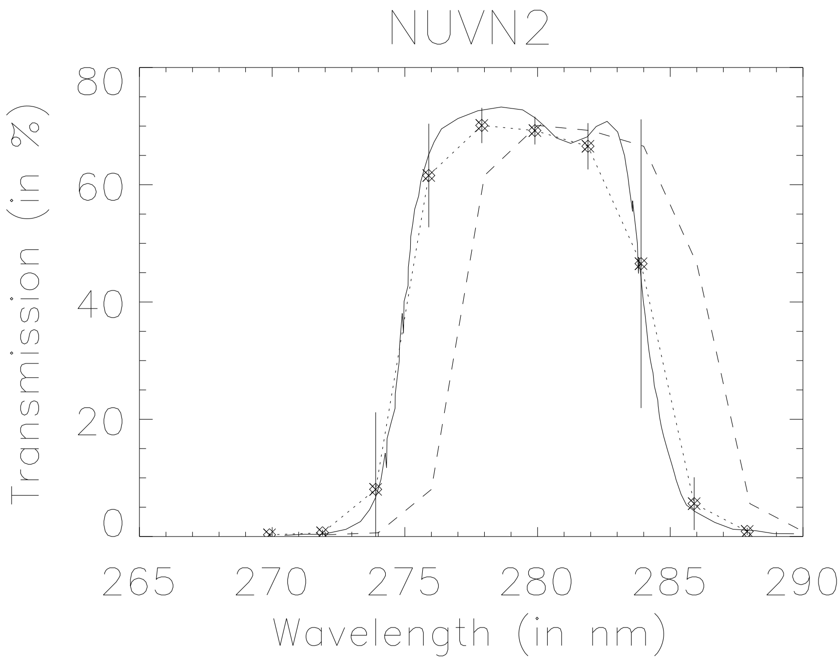
Transmission curve for NUVB15 filter measured at LEOS Laboratory. Solid line: Vendors curve at the centre of the filter. Data Points (diamond): Measurement with the wavelength shifted by +2.5nm (as explained in the text) measured at the edges. Dashed line: Measurement with the wavelength shifted by +2.5nm (as explained in the text) measured at the center.



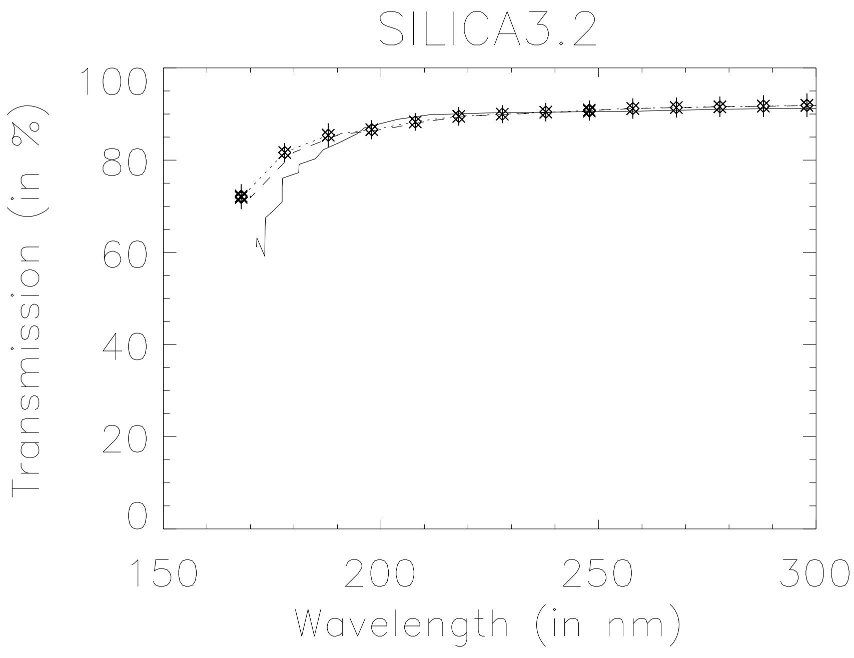
Transmission curve for NUVB13 filter. Solid line: Vendors curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -2.1nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -2.1nm wavelength shift for comparison.



Transmission curve for NUVB4 filter. Solid line: Vendors curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -2.1nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -2.1nm wavelength shift for comparison.



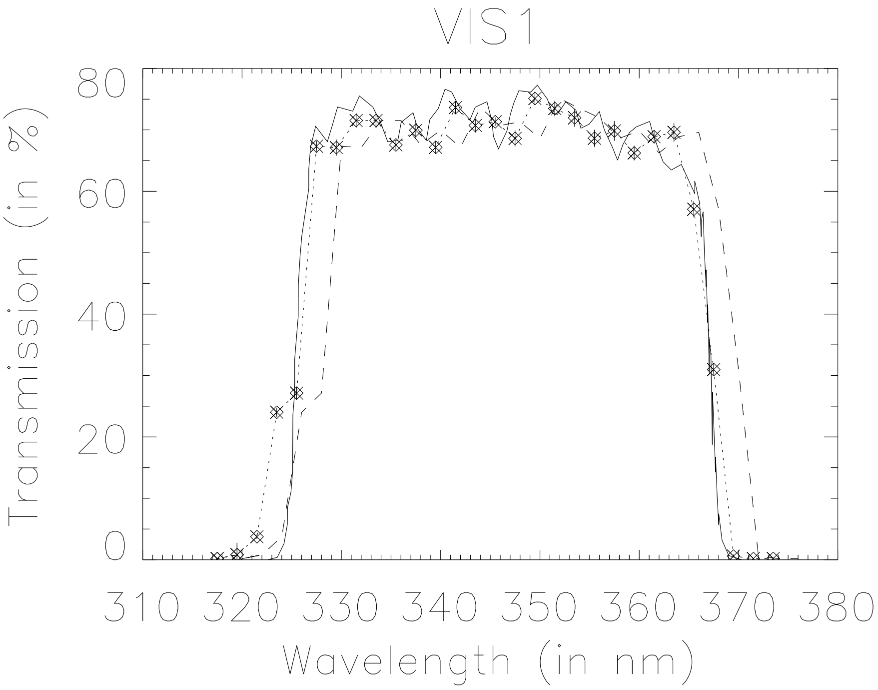
Transmission curve for NUVN2 filter. Solid line: Vendors curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -2.1nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -2.1nm wavelength shift for comparison.



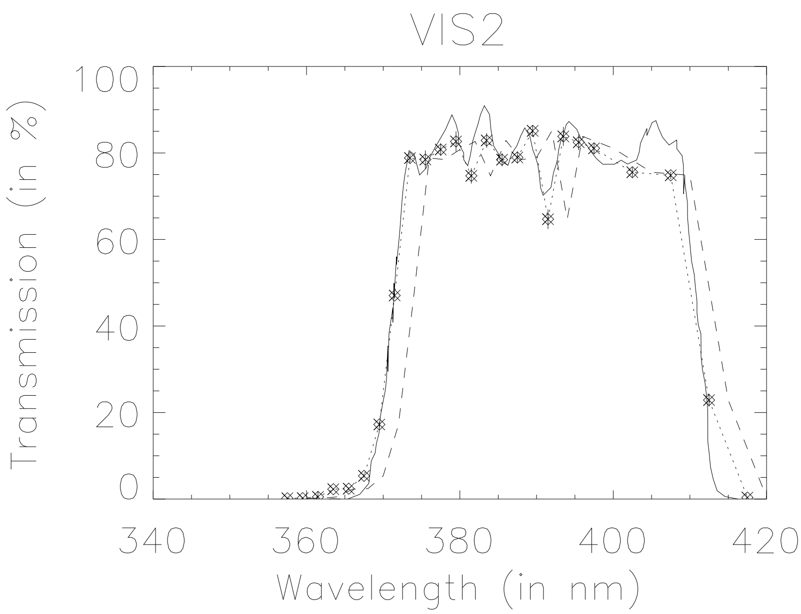
Transmission curve for Silica 3.2mm thickness filter. Solid line: Literature curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -2.1nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -2.1nm wavelength shift for comparison.

Visible – Results:

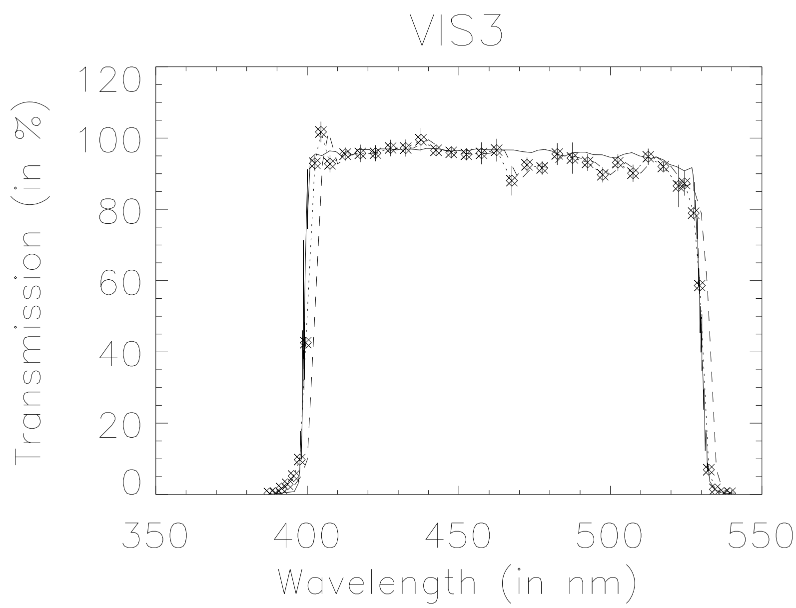
Below figures shows the results for all the FM-Visible filters. Points with error bars are the measured ones where as the solid line are the vendor values for narrow band filters and literature value for the broadband filters. A wavelength offset of -2.5nm has to be added to the experimental values to match with the vendors curve. This offset value was estimated from the VIS2 and VIS3 filter curves. This constant offset is applied to all the filters since the optical setup is same for all of the filter transmission measurement in VIS. All the measurements were carried out at the MGKM laboratory. For NDF, no measurements were carried out and hence not included in this report.



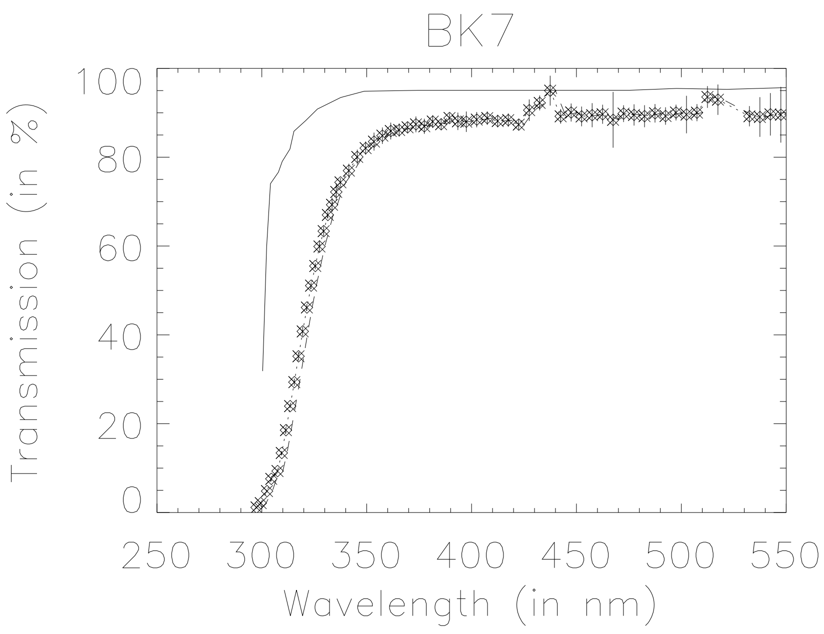
Transmission curve for Visible-1 filter. Solid line: Vendors curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -2.5nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -2.5nm wavelength shift for comparison.



Transmission curve for Visible-2 filter. Solid line: Vendors curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -2.5nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -2.5nm wavelength shift for comparison.



Transmission curve for Visible-3 filter. Solid line: Vendors curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -2.5nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -2.5nm wavelength shift for comparison.



Transmission curve for BK7 filter. Solid line: Literature curve. Data Points connected by dotted line: Measurement with the wavelength shifted by -2.5nm (as explained in the text). Error bars are 3-times the measurement error. Dashed line: Actual measurement without the -2.5nm wavelength shift for comparison.

Appendix C: Focus Shift Results

Focus shift results shows inconsistent results for certain filters. The focus shift measurements will be carried out at the integrated system level for each of the filter to confirm that there are within the ±0.1mm requirement. Those new measurements will be used for the operational purposes.

FUV – Results:
Below figures shows the results for all the FM-FUV filters.

Slot No.	Filter Name	Wavelength (nm)	Exposure Time (sec)	Focus Shift (mm)	Error (mm)	Requirement (mm)	Remarks
4	CaF2-1	180.0	0.5	0.840	0.020	1 ± 0.1	Refer (1)
3	BaF2	180.0	0.5	0.932	0.014	1 ± 0.1	Complied
2	Sapphire	180.0	0.5	1.026	0.018	1 ± 0.1	Complied
6	CaF2-2	180.0	0.5	0.806	0.014	1 ± 0.1	Refer (1)
0	Silica	180.0	0.5	0.918	0.011	1 ± 0.1	Complied

(1) Both CaF2 filters show smaller focus shift than expected.

NUV – Results:
Below Table shows the results for all the FM-NUV filters.

Slot No.	Filter Name	Wavelength (nm)	Exposure Time (sec)	Focus Shift (mm)	Error (mm)	Requirement	Remarks
6	Silica3.0	294.0	2.0	0.518	0.007	1 ± 0.1	Refer (2)
7	NUVB15	218.0	5.0	-11.839	0.005	1 ± 0.1	Refer (3)
0	NUVB13	250.0	3.0	1.281	0.102	1 ± 0.1	Refer (4)
2	NUVB4	265.0	3.0	1.099	0.009	1 ± 0.1	Complied
3	NUVN2	280.0	3.0	1.102	0.010	1 ± 0.1	Complied
4	Silica3.3	294.0	2.0	1.065	0.008	1 ± 0.1	Complied

(2) Very small focus shift. Not consistent with the expected value.
(3) Huge shift inconsistent with what is expected. Independent experiment is being carried out for this filter.
(4) Large shift in this filter even taking into account the error in the measurement.

Visible – Results:
Below Table shows the results for all the FM-Visible filters.

Slot No.	Filter Name	Wavelength (nm)	Exposure Time (sec)	Focus Shift (mm)	Error (mm)	Requirement	Remarks
3	Vis1	330.0	15.0	1.078	0.016	1 ± 0.1	Complied
2	Vis2	380.0	15.0	1.081	0.026	1 ± 0.1	Complied
1	Vis3	420.0	15.0	1.056	0.030	1 ± 0.1	Complied
5	BK7	500.0	15.0	1.109	0.044	1 ± 0.1	Complied
4	NDF	500.0	NA	NA	NA	NA	Refer (5)

(5) NDF measurements need to be carried out.

Appendix D: Wedge Angle Results

FUV – Results:

Below table shows the results for all the FM-FUV filters and for a set of wavelengths.

Slot No.	Filter Name	Wavelength (nm)	Exposure Time (sec)	Wedge Angle (arcmin)	Error (arcmin)	Require ment (arcmin)	Remarks
4	CaF2-1	180.0	1.0	0.493	0.013	3.0	Complied
3	BaF2	180.0	1.0	0.018	0.001	3.0	Complied
2	Sapphire	180.0	1.0	0.058	0.002	3.0	Complied
0	Silica	180.0	1.0	0.014	0.008	3.0	Complied
6	CaF2-2	180.0	1.0	0.857	0.016	3.0	Complied

NUV – Results:

Below table shows the results for all the FM-NUV filters and for a set of wavelengths.

Slot No.	Filter Name	Wavelength (nm)	Exposure Time (sec)	Wedge Angle (arcmin)	Error (arcmin)	Require ment	Remarks
6	Silica3.0	293.0	1.0	0.388	0.007	3.0	Complied
7	NUVB15	210.0	5.0	6.63	0.297	3.0	Refer (1)
0	NUVB13	250.0	1.0	0.006	0.006	3.0	Complied
2	NUVB4	265.0	1.0	0.007	0.007	3.0	Complied
3	NUVN2	280.0	1.0	0.018	0.002	3.0	Complied
4	Silica3.3	293.0	1.0	0.010	0.007	3.0	Complied

(1) Issues with this experiment: The pinhole image was not good with this filter. New measurements are being carried out.

VIS – Results:

Below table shows the results for all the FM-VIS filters and for a set of wavelengths.

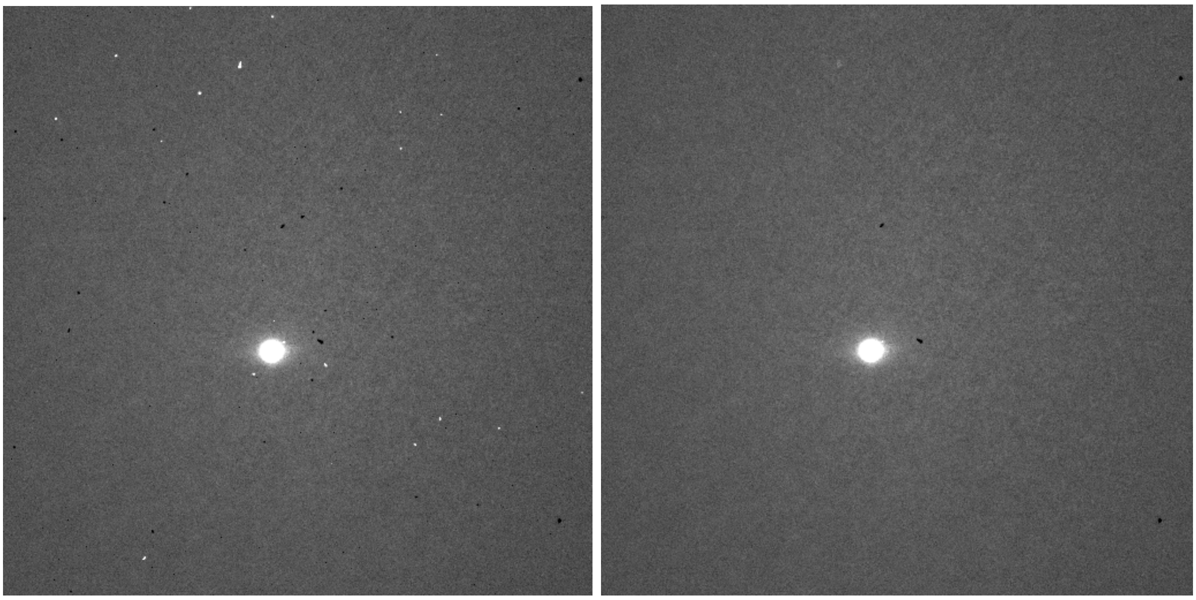
Slot No.	Filter Name	Wavelength (nm)	Exposure Time (sec)	Wedge Angle (arcmin)	Error (arcmin)	Require ment	Remarks
3	VIS1	330.0	1.0	0.035	0.004	3.0	Complied
2	VIS2	380.0	1.0	0.008	0.014	3.0	Complied
1	VIS3	420.0	1.0	0.082	0.034	3.0	Complied
5	BK7	500.0	5.0	0.237	0.002	3.0	Complied
4	NDF	500.0	NA	NA	NA	3.0	Refer (2)

(2) NDF Measurements need to be carried out.

Appendix E: Hot pixel removal

Hot pixels are replaced by using a sigma-filter algorithm (available in ASTROIDL software). This program computes the mean and standard deviation of pixels in a box centered at each pixel of the image, but excluding the central pixel. It then compares the central pixel value with the mean and if it exceeds some # of standard deviations from the mean, it is then replaced by the mean of the box. The mean is taken by excluding the central pixel.

The box size chosen for the EM and FM is 6 and more than 3-times the standard deviation is considered as hot-pixels. Figure 1 shows the raw image and the hot-pixels removed image. Note that this algorithm also corrects for the dead pixels but not the cluster of dead pixels.



<u>Figure:</u> *Left:* Raw image obtained from the SBIG camera. The pin-hole image can be seen as a bigger circle and the hot pixels are seen as bright dots. *Right:* Hot pixels are replaced with a mean of the near-by pixels. The intensity scale is deliberately scaled to make the pin-hole image appear as saturated in order to show the background regions of the image.

Appendix F: Background Subtraction Algorithm

The background subtraction was carried out by choosing an elliptical annular ring around the pin-hole image. The inner radius of the ring is chosen as five times the SIGMA of the pin-hole image and the outer radius is ten times the SIGMA. The mean count value obtained in this region is used as the background. This value was checked against the typical bias counts and matches very well. The background subtraction is chosen in order to minimize any time variation in the dark/bias frames of the SBIG CCD. An elliptical ring is chosen since the pin-hole image is not circular and also the circularity changes with wavelength of interest due to the defocusing effect after the second focusing lens reaches its travel limit. Note that in this far UV wavelength range the focus of the lenses changes quite drastically with wavelength. The steps involved in this procedure are the following:

- A 2D Gaussian fit is carried out to find the approximate maximum position as well as the FWHM.
- Centroid algorithm is used to find the accurate centroid position of the pin-hole image.
- An elliptical annular mask centered on the centroid position estimated from the above set is created. The mean of this region is the back ground. (For the EM as well as FM, it is found that with the inner radius of 5 times the SIGMA and outer radius of 10 times the SIGMA works good).

Figure below shows the hot-pixel removed image along with the annular ellipse. The inner radius of the ellipse in this image is 5-times the SIGMA of the pin-hole image and where as the outer radius is 10-times. The annular region within this bound is deliberately made equal to a large number in order to show them in this image. In reality, this region will be as dark as that of the surroundings.

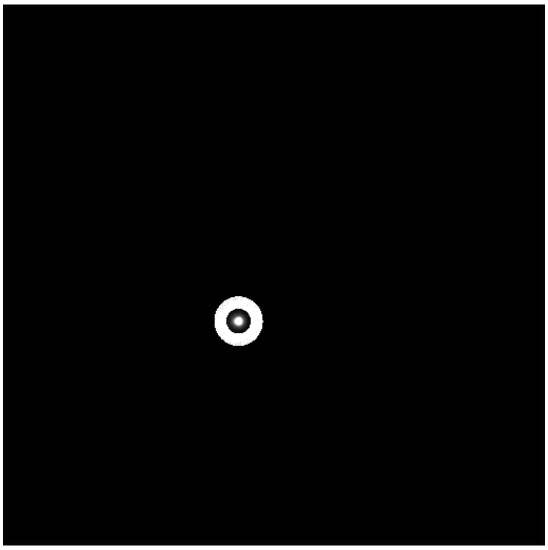


Figure: Hot pixels replaced pin-hole image. The annular ring shown in this image is used for the estimation of the back ground value.

Appendix G: Minimizing the source structures in Spatial Variation

The source structures do not get eliminated fully during the ratio as explained in the spatial variation section of this report. There are also bright patched due to multiple reflections within the filters. This appendix provides the details of how these structures are minimized while obtaining the spatial variation results.

There are two prominent structures seen during the analysis: (i) slit like structures which are seen as bright slits in the open images while it is smeared out in the filter images, (ii) Bright patch structures which are seen in the filter images and absent in the open images. Figure 1 shows an example of these two structures.

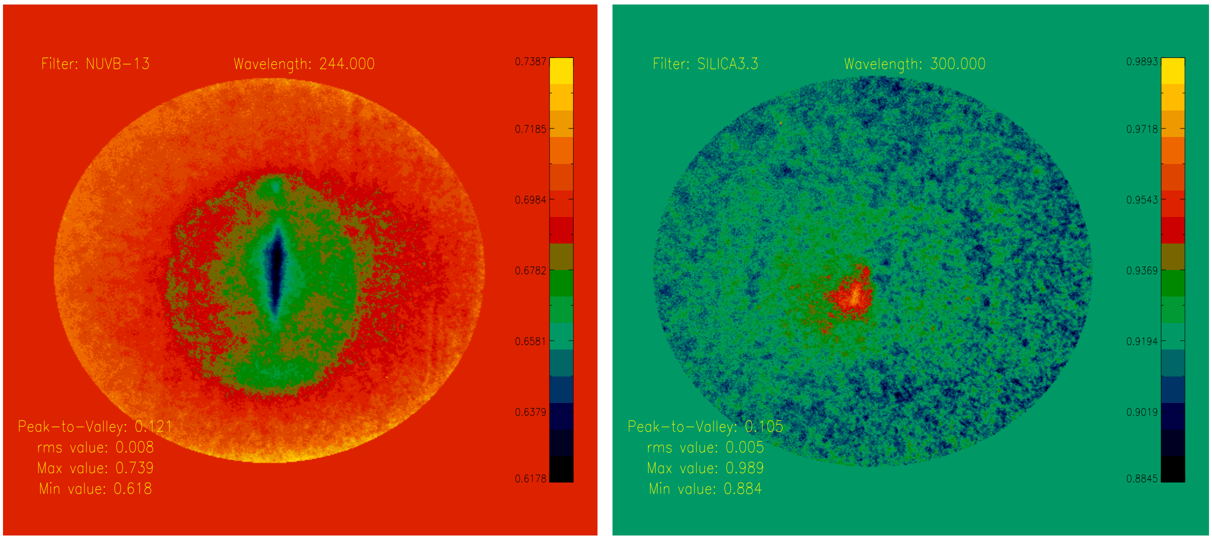


Figure 1: This figure shows the slit structure (left) due to bright slit visible in the open image and the bright patch (right) visible in the filter image. These structures are high in contrast compared to the actual filter spatial variation and hence to be minimized.

(i) Minimizing the Slit structure: The slit like structure showing a minimum in the central region are removed by fitting a one-dimensional Gaussian function + a second order polynomial to take care of the slow variation. A large region around the central portion is chosen and each row within this chosen region is fitting with this function. After obtaining the best fit parameters, the Gaussian alone is regenerated and removed from the input data. The result are then stored in a new file. Figure 2 (left image) shows a sample output of this procedure corresponding to the left image in the figure 1.

(ii) Minimizing the bright patch: The bright patch is selected using a circular region-of-interest (radius say r0). Once the region is chosen, then nine circles of differing radius are created (1.5, 1.7, 1.9, 2.1, 2.3, 2.5, 2.7, 2.9 and 3.1 times of r0). The average transmission values between these circles are estimated (between 1.5 and 1.7; between 1.7 and 1.9; between 1.9 and 2.1 etc.). The variation of these average values follows a straight line and hence a straight line fit was used to fit these variations and found the co-efficients. These co-efficients are then used to find the average transmission values for pixels within the circle radius r0 and replaced. Figure 2 (right images) shows a sample output of this procedure corresponding to the right image in the figure 1.

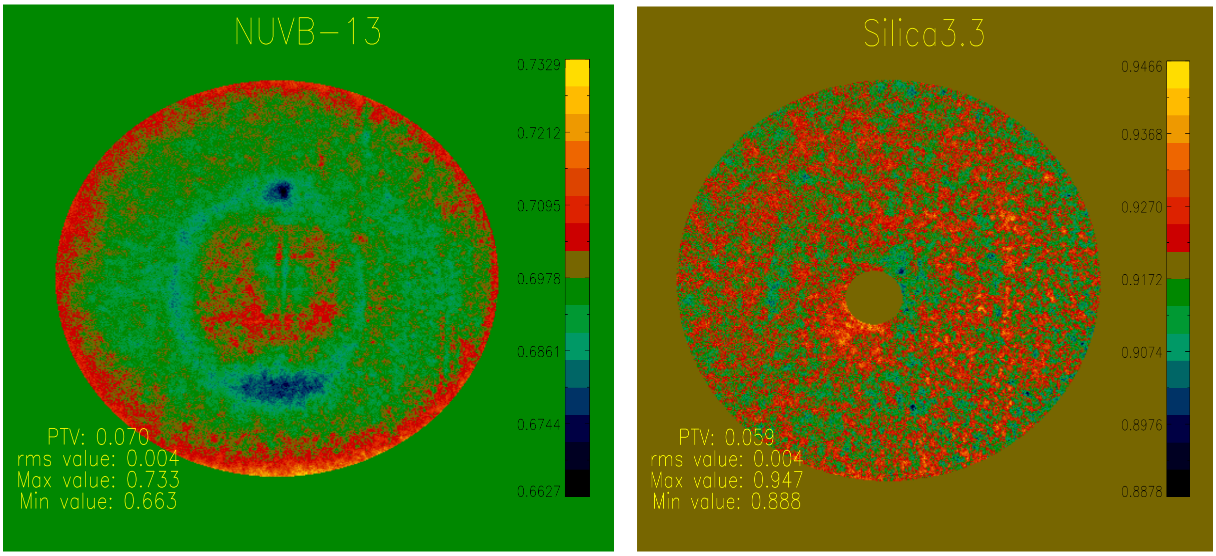


Figure 2: This figure shows the same image as figure 1 but after going through the processing discussed in this appendix. The slit structure (left) and the bright patch (right) which was visible in Figure 1 was minimized using this procedure.