Measuring spectral transmission of optical filters. Theo Scholten, www.astroscape.nl

For measuring and checking the transmission curves of my SII, H-alpha, OIII and RGB optical filters I constructed a simple but effective spectrometer using a replicated transmission grating.

Basic concept of the spectrometer:

The figure below gives a schematic drawing of the spectrometer. The spectrometer comprises two arms under an adjustable angle. The first holds a small white source to illuminate the grating that creates a spectrum. The second captures this spectrum and focuses it onto an image sensor. The filter to be examined is placed in the light path and only transmits part of the spectrum for which it is designed. The ratio of the spectrum with and without the filter results in the transmission curve of the filter.

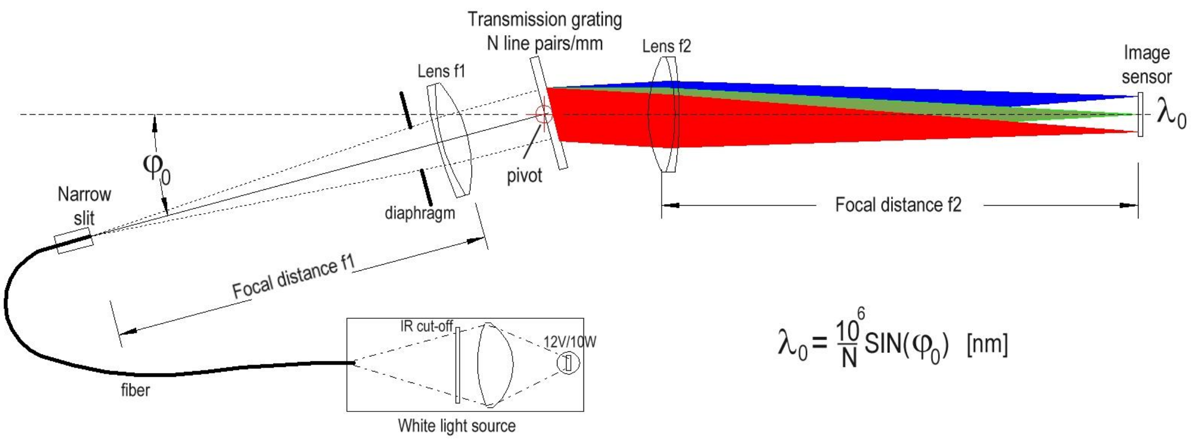

Figure 1. Schematic layout of the transmission grating spectrometer.

Constructural details and some formulas:

The light source is a 10W Tungsten-Halogen lamp focused, using an aspherical condensor lens, on a 0.25mm core plastic fiber that guides the light to a 0.1mm wide slit. To avoid melting the plastic fiber, the white light source contains an IR-cut-off filter (>750nm).

White light exiting the slit is collimated (i.e. made parallel) using an f_1=500mm achromatic lens. An iris diaphragm limits the diameter of the collimated beam to 10-15mm diameter to ensure that it is passed unobstructed from source to detector. The beam hits the grating orthogonally (i.e. along the normal to the surface of the grating). The beam is diffracted by the transmission grating, splitting it in a continuous spectrum of collimated beams with the following relation between wavelength **λ** (in nm) and diffraction angle **φ**:

$$\lambda = 10^6 * \sin(\varphi)/N \ \text{[nm]} \quad \text{or} \quad \varphi = \sin^{-1}(\lambda * N/10^6)$$

Where N is the number of line pairs per millimeter of the grating. I use N=100 or N=300 lp/mm gratings.

The first arm can pivot around the center of the diffraction grating in order to set the central wavelength $\boldsymbol{\lambda_0}$ by setting $\boldsymbol{\varphi_0}$. The second arm also contains an achromatic lens (f_2=500mm). It focuses the beam with the selected φ_0 on the center of the image sensor. I use my CCD-camera for this.

Below is what the real spectrometer setup looks like:

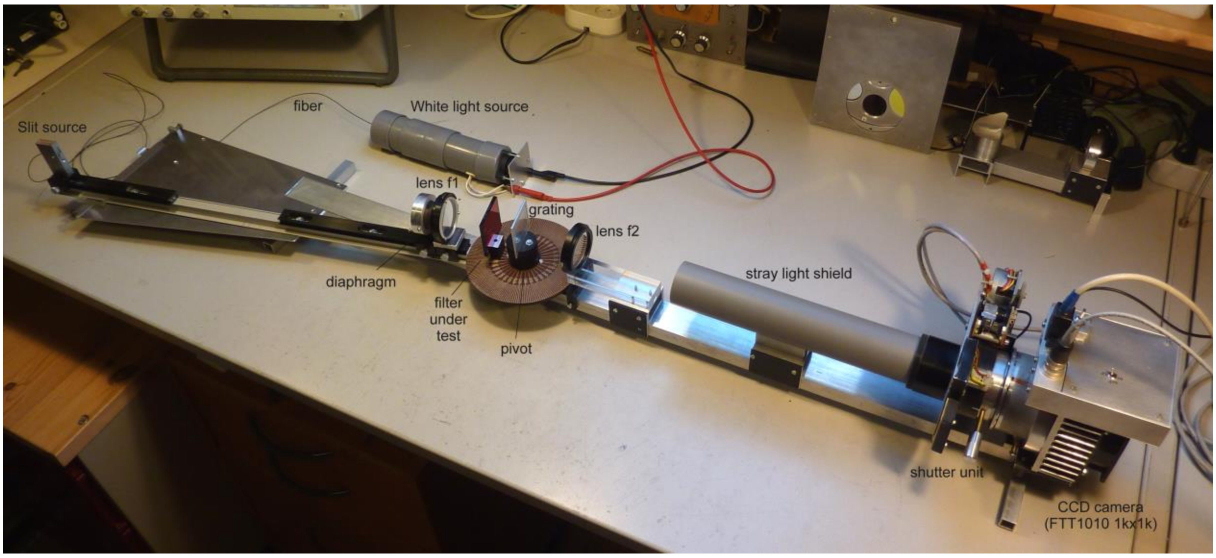

Figure 2. The transmission grating spectrometer using the FTT1010M CCD-camera and a shutter unit. A rectangular H-alpha filter is shown, inserted in the light path between lens f_1 and the grating.

With focal length f_2 large compared to the pixel size **P** [mm] the following approximation for the wavelength change per pixel holds:

$$\Delta\lambda = 10^6/N * P/f_2 \text{ [nm/pixel]}$$

Thus, the wavelength of the spectrum **M** pixels to the left or right of the central pixel p_c is $\lambda_0+M*\Delta\lambda$ or $\lambda_0-M*\Delta\lambda$.

<u>Let's put in some numbers:</u>

With N=100 lp/mm, f_2=500mm and P=0.012mm, $\Delta\lambda$=0.24 nm/pixel.
With a width of the CCD-sensor of 1024 pixels, a range of 1024*0.24=246nm can be covered. Selecting λ_0=580nm at the center position of the image sensor results in covering the 460-700nm range. This requires setting the angle φ_0=3.33º.

With N=300 lp/mm, numbers change by a factor of three: $\Delta\lambda$=0.08 nm/pixel and the range reduces to 82nm. Different φ_0 settings are needed to measure at the OIII wavelength of 500.7nm and the H-alpha and SII wavelengths of 656.3nm and 671.7nm+673.0nm. For centering on OIII, φ_0=8.64º. For covering both H-alpha and SII, φ_0=11.5º resulting in λ_0=665nm and covering the 625-705nm range.

<u>Resolution:</u>

Important is the width **w** of the source, which determines the resolution of the spectrometer:

$$\Delta\lambda_{resolution} = 10^6/N * w/f_1 \text{ [nm]}$$

The transmission curve of a filter with an infinitely narrow transmission band will show up as having a bandwidth of $\Delta\lambda_{resolution}$. Any transmission curve is broadened ('convolved') by $\Delta\lambda_{resolution}$. For a high resolution the width w should be small: For w=0.1mm, f_1=500mm and N=100, $\Delta\lambda_{resolution}$=1.8nm and with N=300 it improves to $\Delta\lambda_{resolution}$=0.6nm.

Please note: For accurate results care should be taken to the following details:

- Collimating arm 1: Use a mirror at the location of the grating to reflect the source onto itself (or, more practically: just beside it on a white paper) and bring it into focus by adjusting the distance from source to lens f_1.
- Collimating arm 2: Set the spectrometer in 'zero-order', i.e. φ_0=0º. Adjust the distance from lens f_2 to the image sensor until the source is in focus.
- Location and orientation of the filter: The filter that is to be measured is preferrably positioned between lens f_1 and the grating (parallel to the grating) or alternatively between grating and lens f_2. At these locations, where the optical path is collimated, the filter, even when tilted, will not affect focus or position of the spectrum on the image sensor.
- Light shielding will be needed in arm 2 to make sure that only light passing the grating is collected.
- Use an illuminated vertical slit instead of a small 'point'-source and average over multiple vertical pixels in the acquired image to improve S/N and lower sensitivity for small vertical deviations in alignment.
- Wavelength calibration: Small deviations in lp/mm value, φ_0-setting and lens f_2 focusing may affect the scale and absolute wavelengths calculated with the formula above. Calibration of the wavelength scale may be needed for accurate results. Use an HeNe laser (632.8nm) and/or a green laser pointer (which is a double YAG-laser, operating at 532.0nm) for this purpose.

Steps for measuring filter transmissions:

1. With φ_0=0º, locate the position of the slit in the image (which may be slightly off center). This is p_c.
2. Set φ_0 to the required λ_0. λ_0 will coincide with the location of the slit in step 1, i.e. with p_c.
3. Acquire the full spectrum without the filter(s).
4. Acquire the spectrum with the filter(s). The ratio of this and of the full spectrum gives the transmission curve.
5. For accurate wavelength calibration: Illuminate the slit (via the optical fiber) using one, or both of the mentioned lasers and locate their pixel positions. These will be more accurate than λ_0.

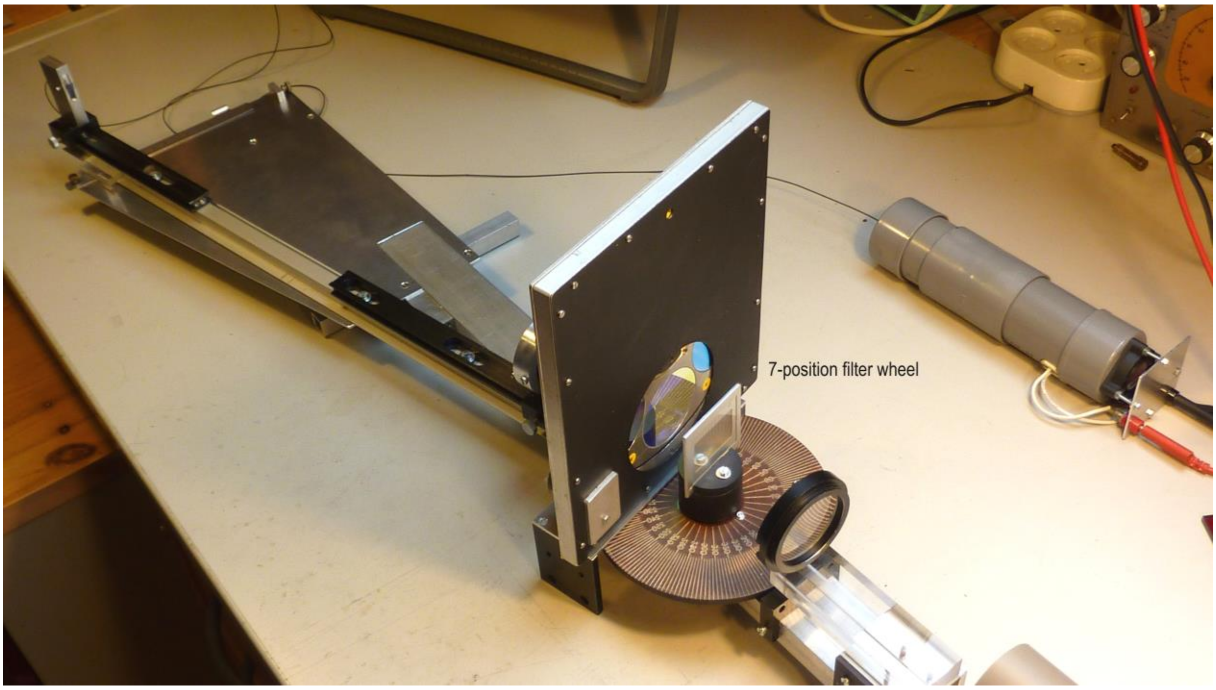

Figure 3. Measuring the SHO and RGB transmission filters of my 7-position filter wheel.

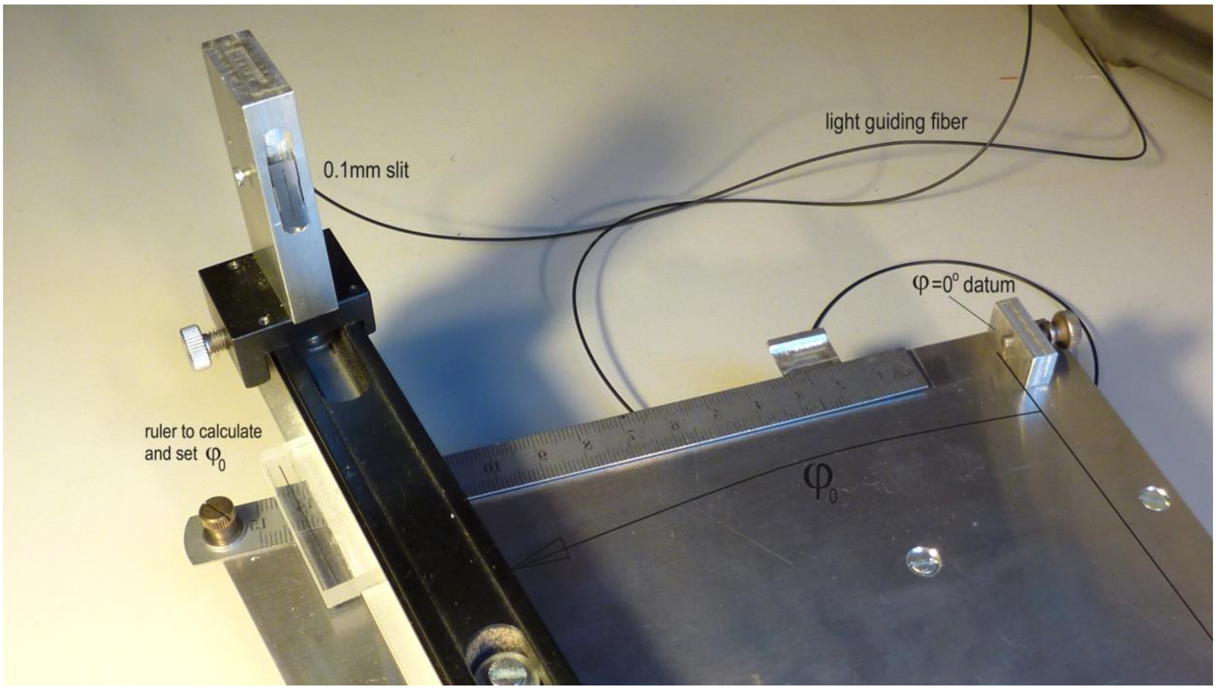

Figure 4. Detail of the slit-shaped source and φ_0 reading.

<u>Some results:</u>

SI filters: I started constructing the spectrometer since I noted that my 11 year old SII filter was under-performing. The spectrum below shows the transmission of this filter (orange) compared to the transmission of a new, more modern SII filter (blue). The position (+/- 1nm) of the SII spectral emission lines are indicated in the graph. Clearly the transmission of the old filter has a bad overlap with the SII spectral emission lines.
Also note that the emission lines are to the left of the transmission envelope of the new filter: This is correct (!) since the transmission curve will shift to shorter wavelength for light rays passing the filter under an increased angle of incidence, as occurs in 'fast' (i.e. low f/D) optics. See further down, the section on fast optics and this wavelength shift.

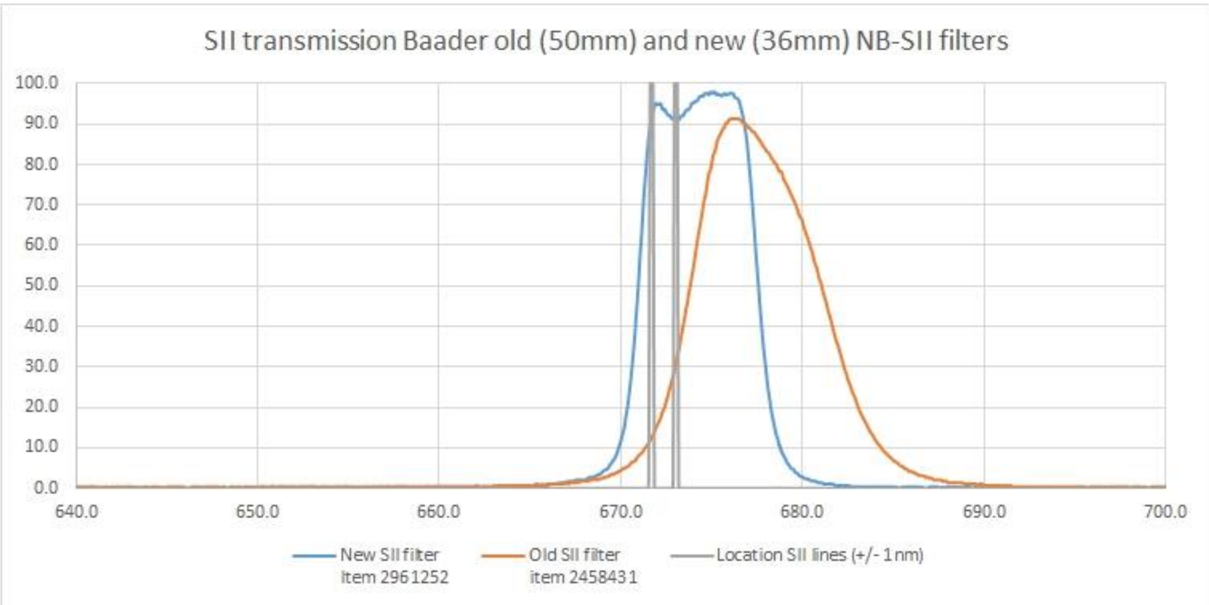

Figure 5. Transmission spectra of two SII filters using the N=300 lp/mm grating. The spectral position of the two emission lines of SII are also indicated (+/-1nm).

RGB-filters: Using 100lp/mm grating and φ_0=3.44º, λ_0=600nm. Wavelength scale calibrated with HeNe laser and doubled-YAG laser pointer.

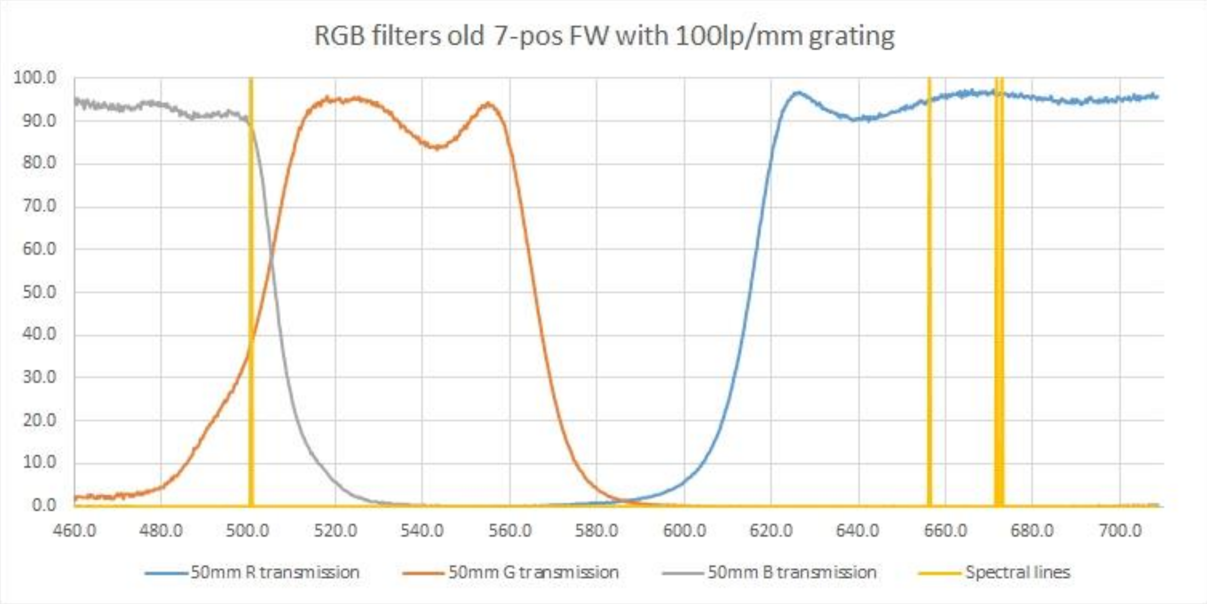

Figure 6. Transmission spectra of Edmund Optics RGB-filters using the N=100 lp/mm grating. The spectral position of SII, H-alpha and OIII emissions are also indicated.

OIII filters: When comparing my old OIII filter (orange) with a new version (blue) it shows that the transmission efficiency is below specification!

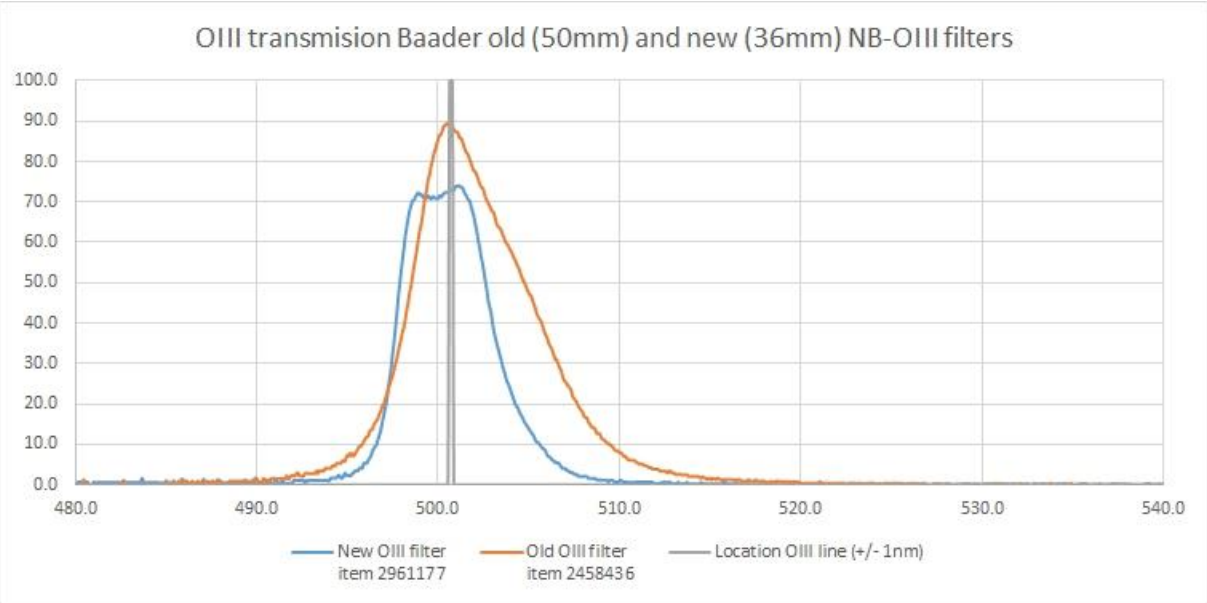

Figure 7. Transmission spectra of two OIII filters using the N=300 lp/mm grating. The spectral position of the emission line of OIII is indicated (+/-1nm).

Filters for fast optics:

Interference filter characteristics depend on the angle of incidence α. In general the transmission curve shifts towards a shorter wavelength for larger angles. When using the filters with 'fast'-optics, i.e. with small f/D-ratios and that contain contributions with large α, it is important that the spectral line(s) remains well within the transmission band of the filter: Filters are designed and manufactured such that with normal incidence (α =0º) the spectral line of interest is on the short wavelength side of the

transmission envelope. This leaves room for the transmission envelope to shift to shorter wavelengths with increasing angle of incidence.
The shift is larger for filters with longer wavelength and, thus, less critical for OIII filters.

Below are spectra tranmission curves of SII and H-alpha filters at α =0º and at maximum angles that occur for f/D=4 and f/D=3, i.e. α=atan(0.5*D/f)=7.1º for f/D=4 and 9.5º for f/D=3. The spectra are obtained by rotating the filter from its perpendicular orientation (i.e. α=0º) to the required angle α. For both filters the spectra line(s) remain well within the envelope.

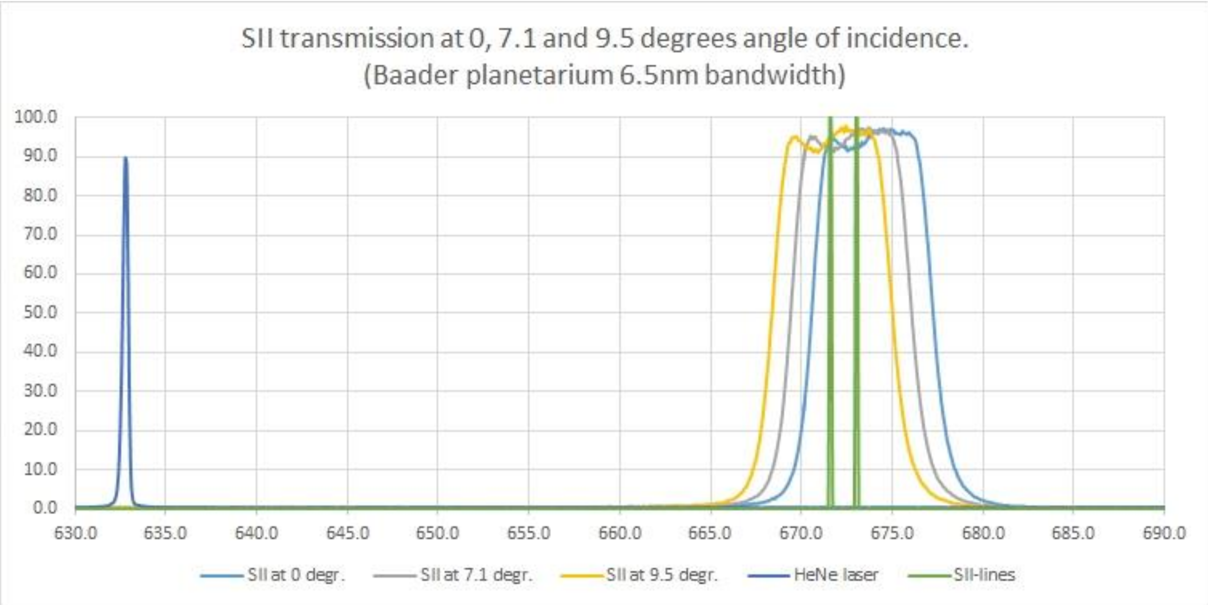

Figure 8. Transmission spectra for an SII-filter at angles of incidence that occur for f/D=4 and f/D=3. The wavelength scale is calibrated using an HeNe-laser (left: 632.8nm). The spectral position of the emission lines of SII are indicated (+/-1nm).

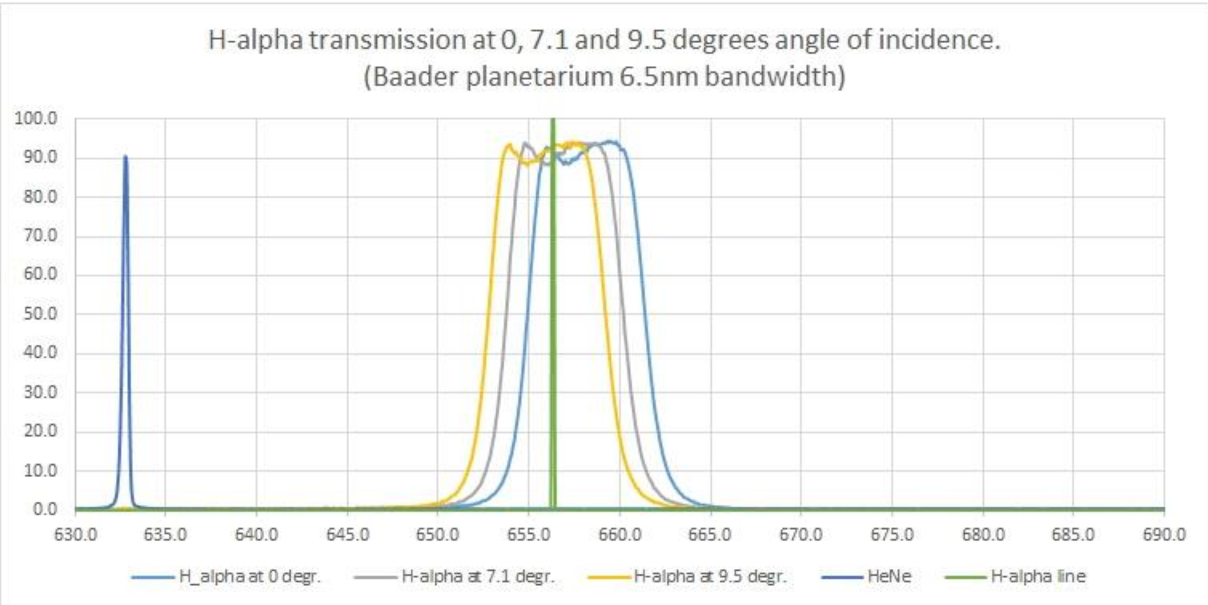

Figure 8. Transmission spectra for an H-alpha filter at angles of incidence that occur for f/D=4 and f/D=3. The wavelength scale is calibrated using an HeNe-laser (left: 632.8nm). The spectral position of the H-alpha emission line is indicated (+/-1nm).