Exposure Time Calculator for LUCI
- USER MANUAL -

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Abstract

The exposure time calculator (ETC) roughly calculates the exposure time of LUCI at the Large Binocular Telescope (LBT). There is a wide choice of different model spectra available (e.g. different main sequence stars). It is also possible to select a blackbody spectrum or a single-line spectrum as an object spectrum.
The main calculations are written in Python and the user interface is web-based. The web interface provides an additional graphical output that shows the SNR versus Wavelength in spectroscopic mode or SNR vs. exposure time in case of a selected imaging mode.
This document presents the basics of the exposure time calculator. The formulae of the ETC and the main characteristics of LUCI are described in detail.

1 Basics

1.1 List of Abbreviations and Acronyms

AO	adaptive optics
CWL	central wavelength
DARK	dark current
DIT	detector integration time
e.m.	electro magnetic
ETC	exposure time calculator
EW	entrance window
FWHM	full-width at half-maximum
HTML	hyper text markup language
LBT	Large Binocular Telescope
LUCIFER/LUCI	LBT NIR Spectroscopic Utility with Camera and Integral Field Unit for Extragalactic Research
PSF	point spread function
QE	quantum efficiency
RON	readout noise
SNR	signal-to-noise ratio
SNR_τ	signal-to-noise ratio for exposure time τ
$\mathrm{SNR}_{\mathrm{DIT}}$	signal-to-noise ratio for one DIT

1.2 The Exposure-Time-Calculator

1.2.1 The Formulae

This program will be used by observers for scheduling their observations with LUCI. The following fixed parameters

- telescope (transmission, light-collecting area, reflectivity, ...)
- transmission of the instruments (entrance window, lenses, ...)
- quantum efficiency (QE) of the detector

and user-defined parameters

- object (geometry, spectrum, magnitude)
- camera (scale)
- filter
- grating, slit width (spectroscopic mode)
- atmospheric conditions (airmass, water vapor, sky background, seeing)
- adaptive optics (is loop closed, Strehl ratio)
- exposure parameters (detector integration time, total exposure time)
- signal-to-noise ratio

are used to calculate two auxiliary values:

$$\mathrm{E} = \mathrm{T_{atm}} \cdot \mathrm{T_{tel}} \cdot \mathrm{T_{inst}} \cdot \mathrm{T_{filt}} \cdot \mathrm{QE} \tag{1}$$

$$\mathrm{F} = \mathrm{F_0} \cdot 10^{-\frac{\mathrm{mag}}{2.5}} \tag{2}$$

$\mathrm{F_0}$: flux density for Vega at $\lambda = 550\,\mathrm{nm}$
$\mathrm{F_0} = 3.56 \cdot 10^{-11} \frac{\mathrm{W}}{\mathrm{m^2 \cdot nm}}$ [FLUX95]
mag : magnitude of the object
QE : quantum efficiency of the detector
$\mathrm{T_{atm}}$: transmission of the atmosphere
$\mathrm{T_{tel}}$: transmission of the telescope
$\mathrm{T_{inst}}$: transmission of the instrument (without any filter and grating)
$\mathrm{T_{filt}}$: transmission of the filter used

The number of photons that are detected per second can be calculated with (1), (2) and the following formula [ESO-HP]:

In the near-infrared regime the SNR for the exposure time DIT is given by the formula:

$$\mathrm{SNR_{DIT}} = \frac{N_{\mathrm{DIT}}}{\sqrt{N_{\mathrm{DIT}} + \mathrm{n_{pix}} \cdot \left(N_{\mathrm{sky}} + \mathrm{DARK_{DIT}} + \mathrm{RON}^2\right)}} \tag{3}$$

Table 1: Formulae for calculating the number of photons from the source

Observing mode	point source	extended source
Imaging	$\frac{N}{\tau} = \frac{\mathrm{F}\cdot\Delta_\mathrm{i}\cdot\mathrm{E}\cdot\mathrm{S}}{\mathrm{P}}$	$\frac{N}{\tau} = \frac{\mathrm{F}\cdot\Delta_\mathrm{i}\cdot\mathrm{E}\cdot\mathrm{S}\cdot\Omega_\mathrm{i}}{\mathrm{P}}$
Spectroscopy	$\frac{N}{\tau} = \frac{\mathrm{F}\cdot\Delta_\mathrm{s}\cdot\mathrm{E}\cdot\mathrm{S}}{\mathrm{P}}$	$\frac{N}{\tau} = \frac{\mathrm{F}\cdot\Delta_\mathrm{s}\cdot\mathrm{E}\cdot\mathrm{S}\cdot\Omega_\mathrm{s}}{\mathrm{P}}$

N : number of photons
P : energy of one photon
S : light-collecting area
τ : exposure time
Δ_i : filter band width
Δ_s : spectral resolution
Ω_i : scale in imaging mode
Ω_s : scale in spectroscopy mode

$\mathrm{DARK}_\mathrm{DIT}$: dark current for 1 DIT
n_pix : number of integration pixels[1]
N_sky : sky signal for 1 DIT
RON : readout noise
$\mathrm{SNR}_\mathrm{DIT}$: signal-to-noise ratio for 1 DIT

In imaging mode the user will be asked for the signal-to-noise ratio for the exposure time τ (SNR_τ). The ETC calculates the necessary exposure time to achieve this SNR_τ (see also formula 3):

$$\tau = N_\mathrm{DIT}\cdot\mathrm{DIT} \qquad \text{and} \qquad \mathrm{SNR}_\tau = \mathrm{SNR}_\mathrm{DIT}\cdot\sqrt{N_\mathrm{DIT}} \tag{4}$$

$$\rightarrow \tau = \left(\frac{\mathrm{SNR}_\tau}{\mathrm{SNR}_\mathrm{DIT}}\right)^2\cdot\mathrm{DIT} \tag{5}$$

τ : total exposure time
DIT : detector integration time
N_DIT : number of detector integrations
SNR_τ : signal-to-noise ratio for exposure time τ
$\mathrm{SNR}_\mathrm{DIT}$: signal-to-noise ratio for one DIT
SNR : signal-to-noise ratio for an exposure time of 1 sec

1.2.2 The Telescope

Mirrors

Both LUCI instruments are going to be first-light instruments for the Large Binocular Telescope (LBT) at the bent Gregorian foci. This means, that the light is reflected three times before entering the cryostats. If we optimistically assume a reflectivity of 90 % for each mirror, we get a total efficiency of 0.729 at the bent Gregorian foci.

Adaptive Optics (AO)

The LBT will provide a deformable secondary mirror for AO observations. For

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[1] In imaging mode n_pix of a point source is calculated within a 2 FWHM diameter aperture: $\mathrm{n}_\mathrm{pix} = \pi\left(\frac{\mathrm{seeing}}{\mathrm{scale}}\right)^2$. In spectroscopic mode the program uses $\mathrm{n}_\mathrm{pix} = 2\cdot\frac{\mathrm{seeing}}{\mathrm{scale}}$. For an extended source n_pix is set to 1 for both dimensions of the source.

this reason the ETC can handle both a seeing-limited PSF and a diffraction-limited PSF (1.2.3). If the loop is closed, different Strehl ratios are possible. This depends on the environmental conditions (seeing, ...). Therefore the value of this parameter is continously changeable.

1.2.3 Point-Spread-Function

Diffraction Limited Mode

In diffraction limited mode with adaptive optics the PSF is approximately composed of two functions:

1. The core: This is an airy function of the telescope

$$I_{\text{Airy}}(r) \sim \frac{D^2}{\lambda^2}\left(\frac{2 \cdot \text{Bessel}(x)}{x}\right)^2 \tag{6}$$

D : diameter of the telescope mirror
μ : observing wavelength
Bessel : the the first kind Bessel function of the order 1.

2. The halo: It is given by a Moffat function

$$I_{\text{Moffat}}(r) = I_{\alpha,\beta}(r) = \frac{\beta - 1}{\pi\alpha^2}\left(1 + \frac{r^2}{\alpha^2}\right)^{-\beta} \tag{7}$$

$I_{\alpha,\beta}(r)$: Intensity at the distance r with parameters α and β
α : Parameter is used to fix the FWHM for a given β
β : Parameter to fix the amount of light in the lobes
r : Distance to the center ($r = \sqrt{x^2 + y^2}$)
$FWHM$: $2\alpha\sqrt{2^{1/\beta} - 1}$

An example of such combined PSF is shown in Figure 1. For comparing the

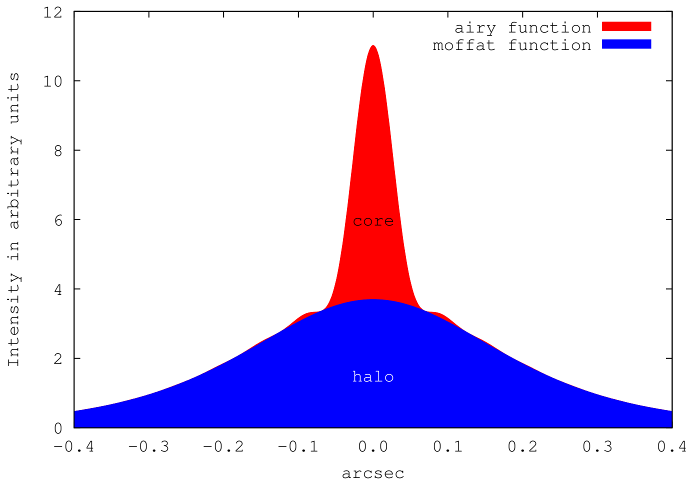

Figure 1: Simplified description of an observed AO-PSF: It is built by a core (Airy function) and a halo (Moffat function).

peak intensity of an ideal diffraction-limited optical system with a real system the *Strehl parameter* was introduced.

$$\text{Strehl} = \frac{I_{\text{obs}}}{I_{\text{theo}}} \tag{8}$$

This parameter is the ratio of the observed peak intensity at the detection plane of a telescope or other imaging system from a point source compared to the theoretical maximum peak intensity of a perfect imaging system working at the diffraction limit. For calculating the fraction of the halo and core component to achieve a certain strehl ratio the parameter *F0* is introduced in this ETC. It has to fulfill the following equation:

$$\begin{aligned} \text{Strehl} &= \frac{I_{\text{obs}}}{I_{\text{theo}}} = \frac{F0 \cdot I_{\text{Airy}}(0) + (1 - F0) \cdot I_{\text{Moffat}}(0)}{I_{\text{Airy}}(0)} && (9) \\ \rightarrow F0 &= \frac{I_{\text{Moffat}}(0) - \text{Strehl} \cdot I_{\text{Airy}}(0)}{I_{\text{Moffat}}(0) - I_{\text{Airy}}(0)} && (10) \\ & && (11) \end{aligned}$$

In this mode the SNR is calculated for a disk with a radius of twice the radius of the airy disk.

Seeing Limited Mode

The PSF in this mode is approximated by a Gaussian-shaped function. In this case the seeing is the FWHM of this function and the SNR is calculated for a disk with a radius of the seeing.

1.2.4 Objects

Besides the choice of the source's size (point source or extended source) the observer can select one out of three different types of spectra:

1. Model spectrum (stellar, galaxy or uniform template)
2. Blackbody spectrum
3. Gaussian-shaped emission line

In imaging mode the stepping of the spectra is 0.5 nm. This stepping is adjusted to the spectral resolution in spectroscopic mode.

Template Spectra

6 different model spectra representing various main sequence stars are available. These are [STERNS]: B0V, A0V, F0V, G0V, K0V, M0V (Figure 2).

Their flux densities are normalized to

$$\text{f}(\lambda = 550\,\text{nm}) = 3.66 \cdot 10^{-11}\ \text{W}\,\text{m}^{-2}\,\text{nm}^{-1} \tag{12}$$

In addition, 4 different galaxy template spectra are available (Figure 3 and [GALAXS]). If a spectrum is allowed to be redshifted the filename must include the phrase 'galaxy' at any position.

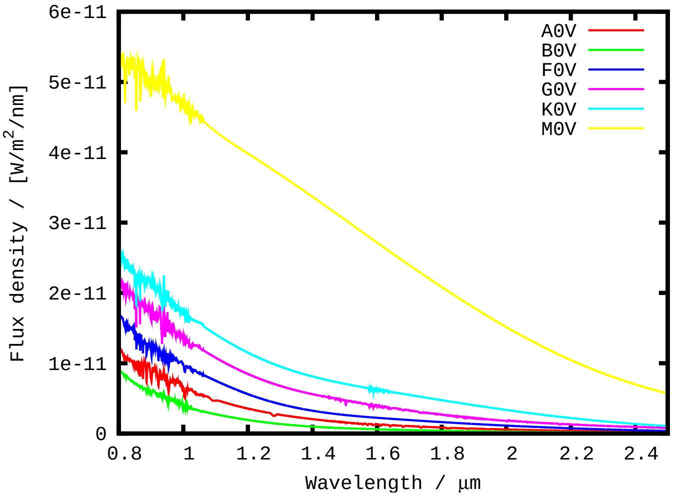

Figure 2: The six available stellar spectra

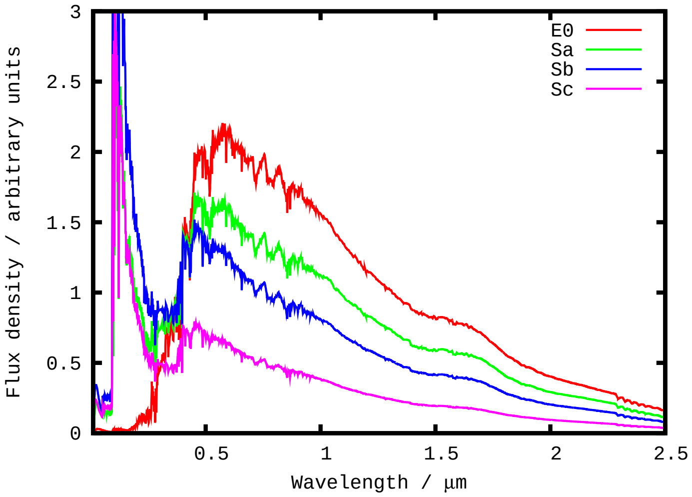

Figure 3: The four available galaxy spectra at redshift z=0.

The transformed spectra are calculated by the definition of the redshift:

$$z = \frac{\lambda - \lambda_0}{\lambda_0} \rightarrow \lambda = (z+1)\lambda_0 \tag{13}$$

z : redshift
λ : measured wavelength
λ_0 : rest wavelength

Finally, a uniform spectrum can be used. The first step of creating such a spectrum (constant flux density for all wavelengths) is to calculate the total flux (in the given band-pass) for a uniform spectrum with an arbitrary flux density. After that the flux is calibrated to the target magnitude given by the user.

Blackbody Radiation

The blackbody spectrum is another option that can be chosen. The flux density is calculated as a function of wavelength (14) for the user-defined temperature (T).

$$f(\lambda) \propto \frac{1}{\lambda^5 \cdot \exp\left(\frac{\mathrm{hc}}{\mathrm{k}\lambda \mathrm{T}_{\mathrm{BB}}}\right) - 1} \tag{14}$$

h : Planck's constant $h = 6,62607 \cdot 10^{-34}$ Js
c : velocity of light $c = 2.9983 \cdot 10^{8} \frac{\mathrm{m}}{\mathrm{s}}$
k : Boltzmann's constant $k = 1,3807 \cdot 10^{-23} \frac{\mathrm{J}}{\mathrm{s}}$
T_{BB} : Blackbody temperature

After that calculation the flux is normalized to the magnitude given by the user.

Gaussian-Shaped Emission Line

The last selectable standard spectrum is a gaussian-shaped emission line. The parameters are: central wavelength, FWHM and total flux. The magnitude of the source is not a free parameter anymore due to the total flux given by the user:

$$f(\lambda) = \mathrm{FLUX} \cdot \frac{1}{\sigma\sqrt{2\pi}} \cdot \mathrm{e}^{-\frac{(\lambda-\Gamma)^2}{2\sigma^2}} \tag{15}$$

σ is given by FWHM/2.35, FLUX the total flux and Γ the central wavelength.

1.2.5 Target Magnitude

The input of the source magnitude (available for template spectra or blackbody only) have to be done in Vega magnitudes.

1.2.6 Filter

LUCI's ETC uses transmission data of all filters measured by the manufacturer [BARR]. They are stored in wavelength steps of 0.5 nm. The transmission curves of these broadband filters are shown in Figure 4. All available filters (including the narrowband filters) are shown in Appendix A. The optical filters U, B, V, R and I can be chosen for the input of the object's magnitude only. They are originally described in steps of 10 nm (U) and 20 nm (B, V, R and I) [FIL-HP]. By linear interpolation the sampling was increased to 0.5 nm.

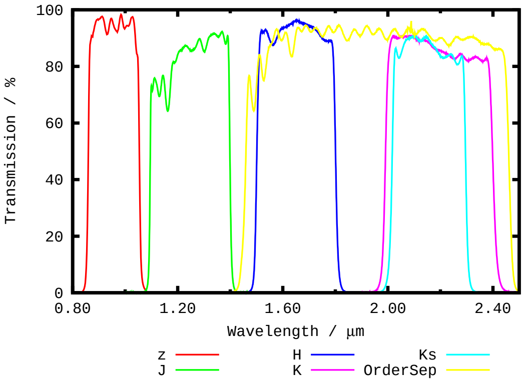

Figure 4: Broadband filters used by LUCI

1.2.7 Cameras

Three different cameras can be used with LUCI. The collimator lenses, mirrors and each camera results in three total efficiencies for each camera. These values are shown in Table 2a. The image scale for all three cameras are listed in Tab. 2b.

Table 2: Efficiencies and image scales of the three cameras

(a) Total efficiencies of the camera-collimator system

Camera	z	J	H	K
N1.8	0.49	0.52	0.57	0.61
N3.75	0.57	0.63	0.68	0.73
N30 (zJ with ADC)	0.37	0.43	0.63	0.68

(b) Image scale of each camera

Camera	Scale ["/pix]
N1.8	0.25
N3.75	0.12
N30	0.015

1.2.8 LUCI 1 and LUCI 2

Both instruments are almost identical. The efficiencies of the two detectors are for the observable wavelength regim nearly constant at about 83%. Both cryostats are equipped with an entrance window tilted by 15°. It reflects the visible light to a wavefront sensor. Each window has a different coating with different cut-on wavelengths (See also Appendix C for the wavelength plots.):

1.2.9 Gratings

Three gratings are installed in LUCI. All of them were tested for their efficiencies by the manufacturer. The company measured in a Littrow setup. LUCI reaches

Table 3: Cut-on wavelengths of the LUCI instruments

	LUCI 1	LUCI 2
50% cut on	882 nm	955 nm

about 90% ([FDR-OP]) of the nominal efficiencies because it is not working under Littrow conditions. See Appendix B for the plots.

- **High-Dispersion grating (HD-grating)** with 210 l/mm (LUCI 1+2)
- **H+K-grating** with 200 l/mm (LUCI 1+2)
- **Ks-grating** with 150 l/mm (LUCI 1)
- **AO-grating** with 40 l/mm (LUCI 2)

1.2.10 Water vapor in the Atmosphere

The water vapor in the atmosphere is the main reason for absorbing light in the near-infrared and infrared. The transmission of light for three different water-vapor levels in the wavelength range from 0.9 µm to 2.5 µm is shown in Figure 5. The transmittance of the atmosphere for 1 mm, 1.6 mm and 3 mm water vapor [TRANSA] is displayed. In the ETC three different values for the water vapor can be selected: 1.0 mm, 1.6 mm and 3.0 mm.

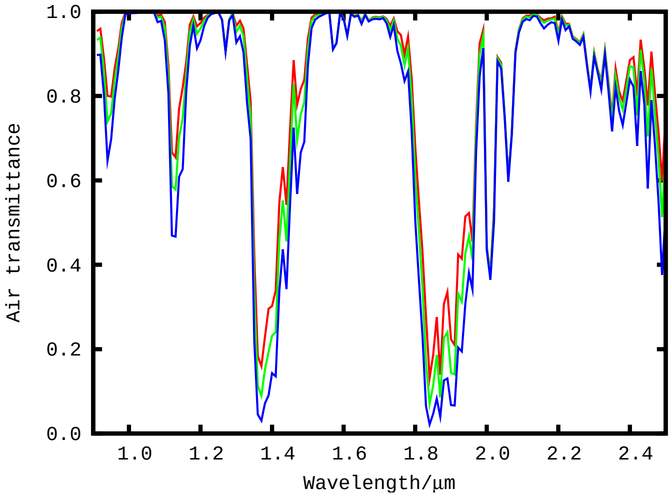

Figure 5: Transmittance vs. wavelength for three different water vapor levels.

1.2.11 Airmass

The airmass is an additional parameter which influences the transmission. The ETC allows six different values for the airmass: 1.00; 1.25; 1.50; 1.75; 2.0; 2.5 The Airmass (AM) scales the number of photons from the sky background with

$$-2.78719\cdot10^{-4}\cdot AM^3-6.53841\cdot10^{-2}\cdot AM^2+1.11979\cdot AM-5.52132\cdot10^{-2} \quad (16)$$

It is a polynomial fit to observed sky brightnesses from [SKYREF]. For small zenith distances ($< 40°$) it is similar to the *van-Rhijn's function* (formula 17).

1.2.12 Sky Background

The sky background in near-infrared regime can rapidly change within hours or even minutes. For that reason the observer can choose between three different possibilities of sky background templates..

Sky Brightness given by the User

The observer can set a brightness of the sky in $\frac{\mathrm{mag(VEGA)}}{\Box\mathrm{arcsec}}$ for the zenith. It is the brightness of the sky for the filter used for the observation.

Background File

Another option is a file. This file contains data from sky background measurements at Mauna Kea for 1.6 mm water vapor and the selected airmass (see Fig. 6).

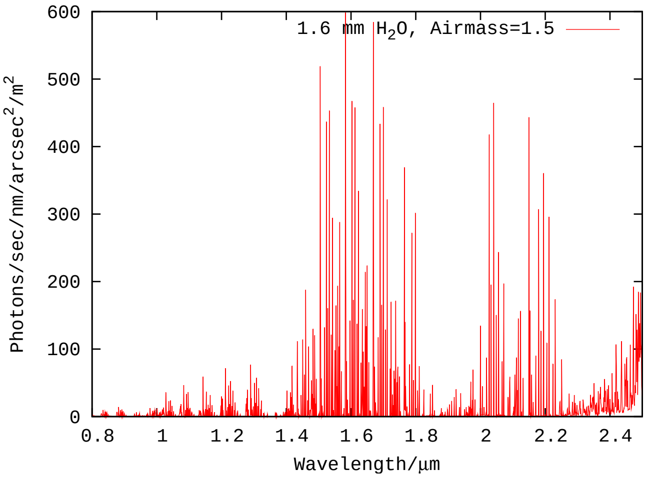

Figure 6: Sky spectrum measured at Mauna Kea for 1.6 mm water vapor and an Airmass of 1.5 [SKYBA]

Theoretical Background Spectrum

A theoretical spectrum is the last possibility for choosing a sky background. This spectrum is shown in Figure 7.

The fundamental parts of this calculation are the OH-line database [OH-LIN, ROUS00] and the transmission data of the atmosphere [AIRTRA]. The ratio of intensities for two lines may change during the night or from observation to observation. This is the reason why it is possibile to change the relative intensities via an ini-file. The predefined values are adjusted to Mauna Kea's night sky spectrum [SKYBA]. For modeling the sky background, we assume:

- OH-line absorption due to the light travel through the atmosphere, scaled with T

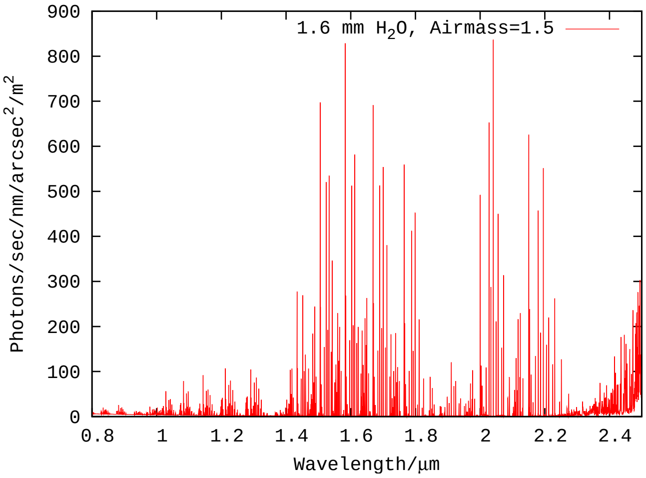

Figure 7: A synthetic spectrum of the sky background

- thermal emission of a blackbody with a temperature of 250 K, scaled with (1-T)
- zodiacal emission (a blackbody spectrum; T=5800 K)
- increasing intensity with larger zenith distances (described by the *van-Rhijn's function*)

Then the sky background can be described as:

$$N_{\text{sky}} = \frac{\mathrm{T} \cdot OH + (1 - \mathrm{T}) \cdot BB_{250\,\mathrm{K}} + BB_{5800\,\mathrm{K}}}{\sqrt{\left(1 - \left(\frac{\mathrm{R}}{\mathrm{R+h}}\right)^2 \cdot \sin^2 \mathrm{z}\right)}} \tag{17}$$

N_{sky} : number of photons from sky background
T : transmission of the atmosphere
OH : intensity of the OH-line
BB_x : blackbody with a temperature x
R : earth radius (∼ 6378 km)
h : hight of emitting layer (∼ 100 km)
z : zenith distance

1.2.13 Slit Width and Slit Transmission

Slit Width
Different slit widths between 0.25" and 2.00" (0.08" and 0.13" in diffraction-limited mode) can be selected. If the width is smaller than the scale of the camera used the width is set to the scale of the camera.

Slit Transmission
First of all the program calculates the number of photons reaching the slit. After that it computes the number of photons behind the slit. For a point-like source

it assumes a PSF like a Gaussian or a Moffat + Airy disc. The hatched area in Figure 8 is the relevant area for transmission. The transmitted photons are split into the pixels 1 - 5 (see bottom of Figure 8). For example: if 18 photons are passing the hatched area of the slit, the light will be split up to 4.5 pixels. Pixel 1, 2, 3 and 4 will detect 4 (18/4.5=4) photons each. The fifth pixel will count 2 photons.

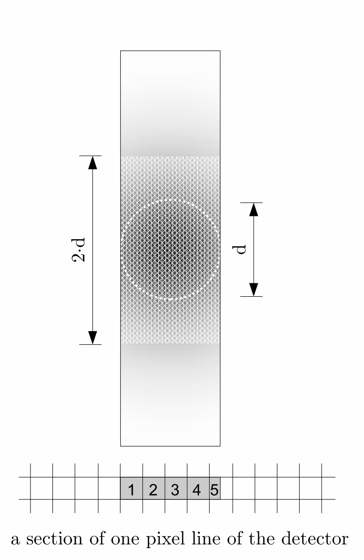

Figure 8: *Top:* Sketch of a slit. The hatched area is used to calculate the transmission of the slit. The parameter d depends on the observing mode. For seeing-limited mode it is the FWHM of the seeing. In diffraction-limited mode it is the diameter of the first minimum of the airy disk. *Bottom:* The calculated photons are split into the shaded pixels.

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A Filter Curves

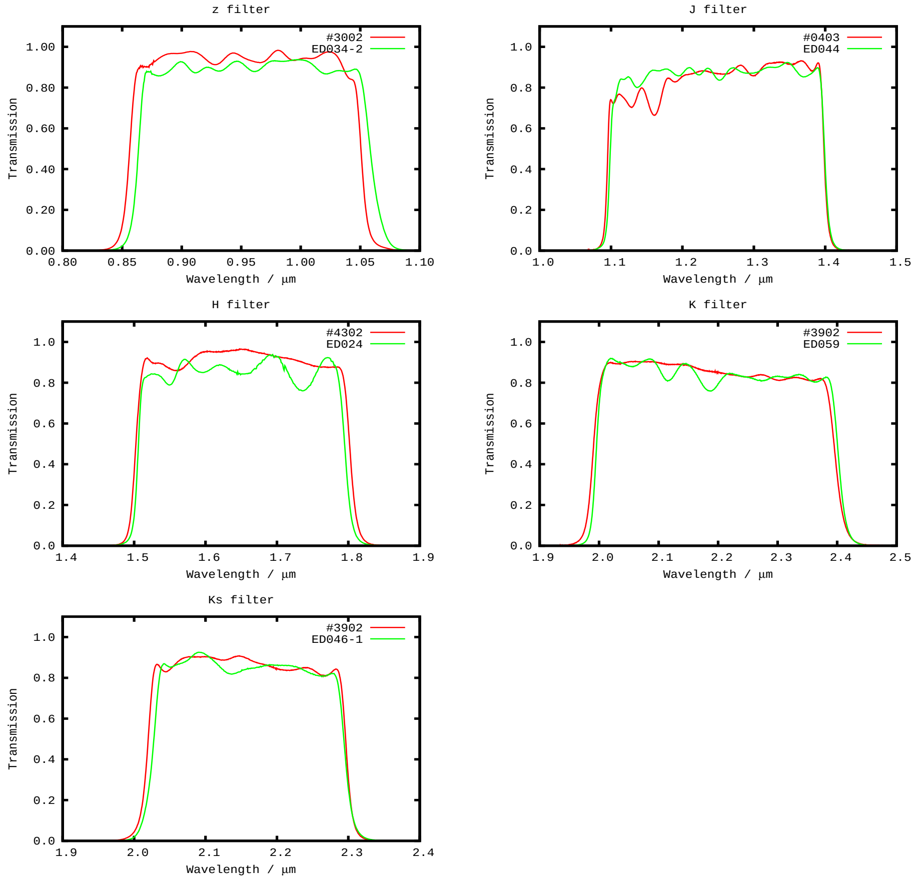


Figure 9: Filter curves of broad-band filters (Part 1)

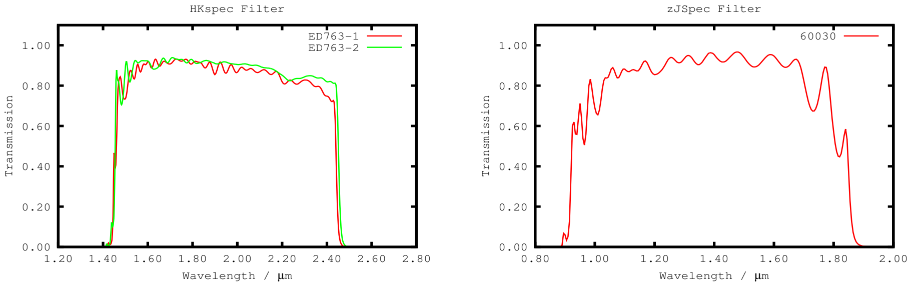


Figure 10: Filter curves of broad-band filters (Part 2)

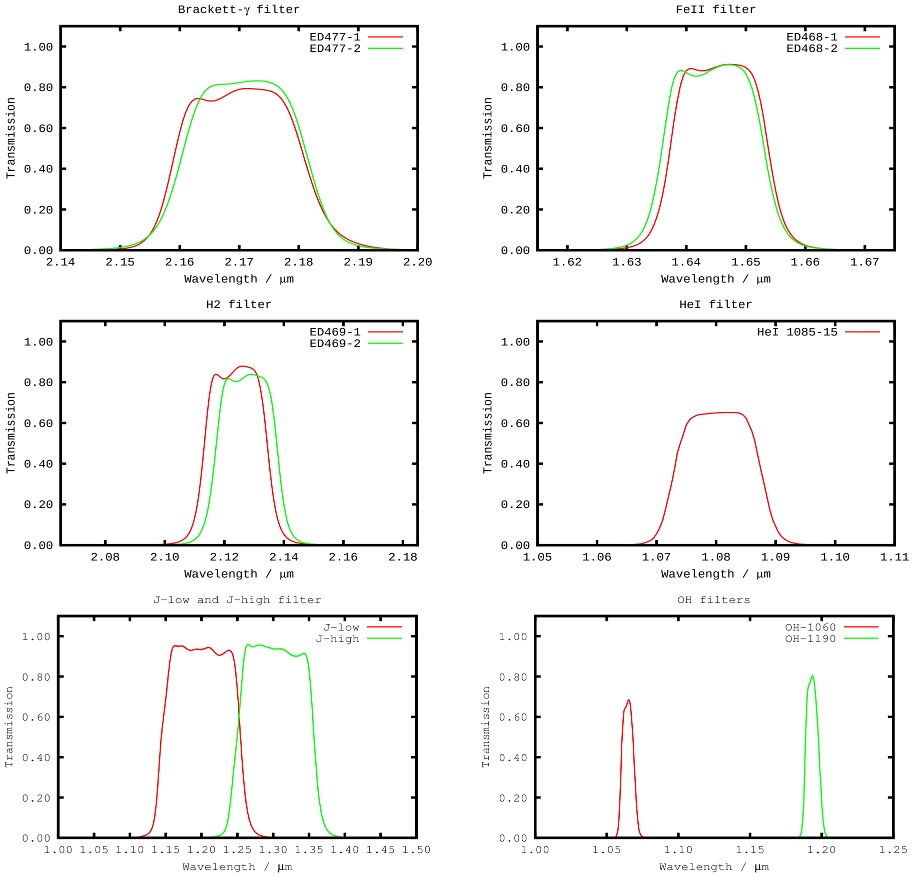


Figure 11: Narrow-band filter curves (Part 1)

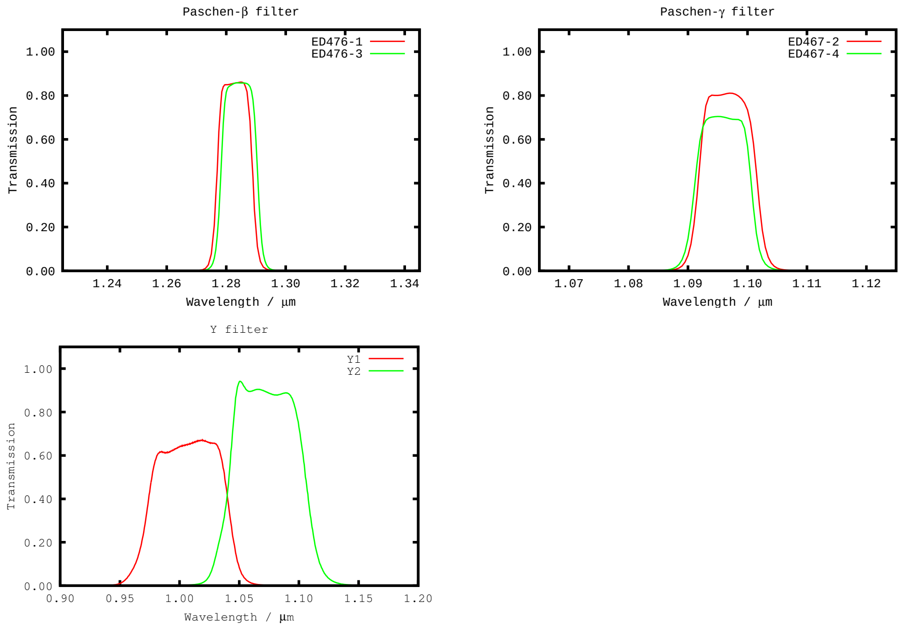
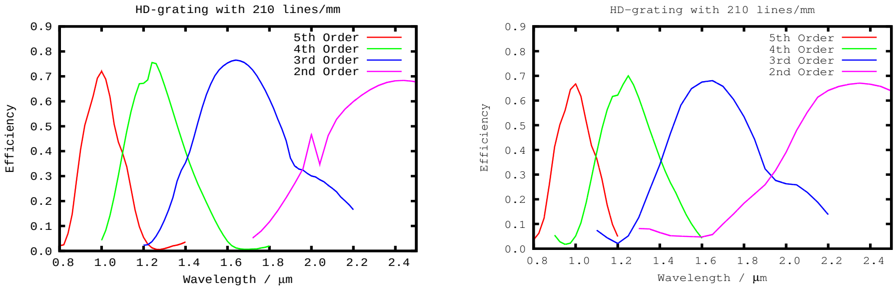
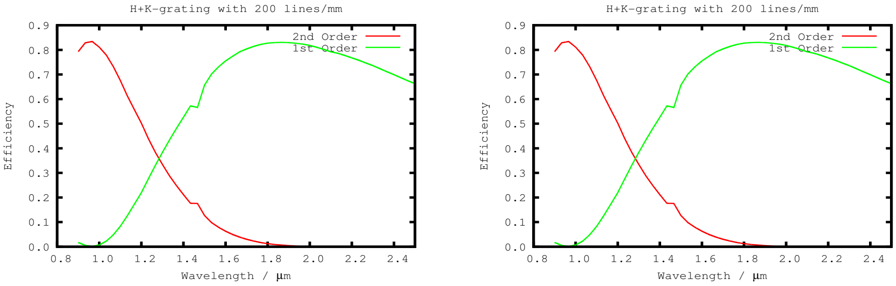


Figure 12: Narrow-band filter curves (Part 2)

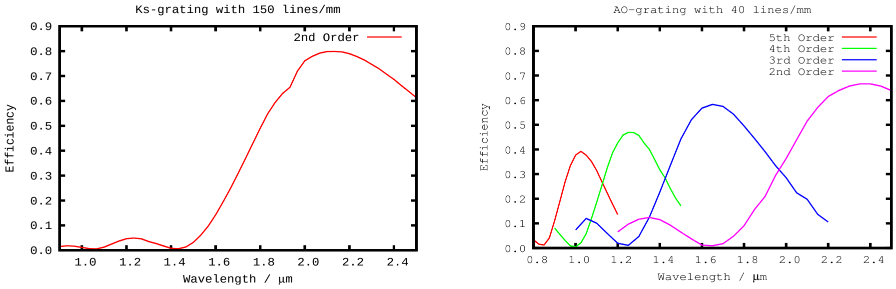
B Gratings



(a) LUCI 1 (b) LUCI 2



(c) LUCI 1 (d) LUCI 2



(e) LUCI 1 (f) LUCI 2

Figure 13: The efficiencies of the gratings vs the wavelength for the Non-Littrow setup in LUCI. The different orders of each grating are color coded.

C Entrance Windows

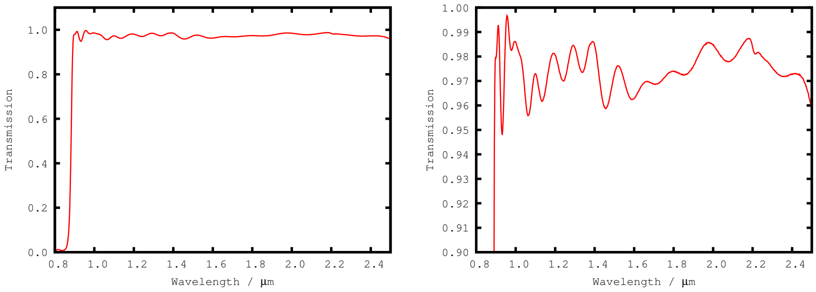


Figure 14: The measured transmission of the entrance window for LUCI 1. *Left:* The whole transmission curve from zero transmission to full transmission 1. *Right:* The transmission curve zoomed-in to a transmission from 0.80 to 1.00.

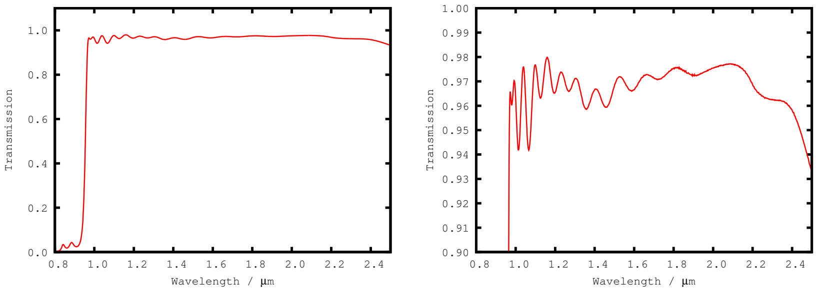


Figure 15: The measured transmission of the entrance window for LUCI 2. *Left:* The whole transmission curve from zero transmission to full transmission 1. *Right:* The transmission curve zoomed-in to a transmission from 0.80 to 1.00.