E-ELT Spectroscopic ETC: Detailed Description

Jochen Liske

Based on a document originally written by Pascal Ballester, Andrés Jordán, Markus Kissler-Patig & Jakob Vinther.

1.   Preliminaries

As of Jan 2008 there exist two E-ELT ETCs. This document describes the new spectroscopic E-ELT ETC. This new ETC obsoletes the spectroscopic mode of the original, first E-ELT ETC. The imaging mode of the original, first ETC remains 'valid' and is described elsewhere.

Generally, a S/N calculation depends on a large number of parameters. To separate those parameters that are user inputs from those that are fixed, we use blue text to mark the user input parameters (and the available options for the parameter where applicable).

2.   Definitions

This section defines all parameters, symbols, terms, units and formulae needed for the S/N calculation. More detailed explanations follow in Section 3.

- $m_{\rm obj}$: Object magnitude (for a point source) or object surface brightness (for an extended source) in a specified band (options: U–Q) and magnitude system (Vega or AB). [mag or mag/arcsec^2]

- $F_0 \equiv 10^{-Z}$: Photometric zeropoint. [W/m^2/μm]

    May be either Vega or AB. The various values for the different bands are listed in Table 1.

- $F_{\rm obj}$: Object flux (point source) or surface brightness (extended source) at the top of the atmosphere. [W/m^2/μm or W/m^2/μm/arcsec^2]

    $F_{\rm obj} = F_0 10^{-0.4\,m_{\rm obj}}$.

    This formula is only strictly true for the case of a uniform flux distribution. Otherwise $m_{\rm obj}$ is used to normalise the flux distribution so that the distribution's integral over the band is equal to the flux given by $m_{\rm obj}$. Instead of $m_{\rm obj}$ the user can also directly specify $F_{\rm obj}$ [mJy or mJy/arcsec^2].

- Observatory site: Paranal-like or High and Dry.

  The choice of site affects the atmospheric emission (only at mid-IR wavelengths) and transmission. Site parameters are listed in Table 2.

- χ: Airmass.

  Options: 1, 1.15, 1.5 or 2. Affects the atmospheric emission (only at mid-IR wavelengths) and transmission.

- D: Telescope diameter. [m]

  Options: 8.2, 30 or 42 m. Note that changing this parameter only affects the size of the photon collecting area but *not* the PSF.

- A: Photon collecting area of the telescope. [m^2]

  $A = \frac{\pi}{4}(D^2 - d^2)$, where d is the diameter of the central obstruction. We assume $d = 0.28\,D$, i.e. that the central obstruction reduces the unobscured collecting area by 8%.

- AO mode: Seeing limited (i.e. no AO), Ground Layer AO (GLAO) or Laser Tomography AO (LTAO). Affects the PSF.

- R_{ref}: Radius of the circular S/N reference area. [mas]

  Options: various values in the range 2.2–1000 mas.

- Ω: Size of the S/N reference area. [arcsec^2]

  $\Omega = \pi R_{\mathrm{ref}}^2 / 10^6$.

- N_{spec}: Number of individual spectra on the detector over which the light from the S/N reference area is spread. This may be equal to the number of separate spatial elements (spaxel) in the S/N reference area.

- λ_{ref}: Observing wavelength, i.e. wavelength at which the S/N is calculated. [μm]

  The ETC actually calculates and plots the S/N as a function of wavelength centered on λ_{ref}.

- R: Spectral resolution. Must be in the range 100–100 000.

- $\Delta\lambda$: Wavelength range that is used for the integration over wavelength. [μm]

  Set equal to a resolution element: $\Delta\lambda = \lambda_{\mathrm{ref}}/R$. It is assumed that $\Delta\lambda$ is sampled by 2 spectral pixel.

- ξ: Atmospheric transmission.

  Depends on site, airmass and λ_{ref} and has two components, one due to molecular absorption and one due to scattering: $\xi = \xi_{\mathrm{abs}}\,\xi_{\mathrm{sc}}$. Details are given in Section 3.

- $\hat{F}_{\mathrm{obj}}$: Object flux (point source) or object surface brightness (extended source) at the telescope entrance. [W/m^2/μm or W/m^2/μm/arcsec^2]

  $\hat{F}_{\mathrm{obj}} = \xi F_{\mathrm{obj}}$.

- ϵ: Total efficiency.

  Set to 0.25. This is the ratio between the number of detected photo-electrons and the number of photons incident at the telescope entrance, i.e. it includes the telescope, instrument and detector, but excludes the atmosphere.

- E_γ: Photon energy at λ_{ref}. [J/γ]

  $E_\gamma = 1.985 \times 10^{-19}/\lambda_{\mathrm{ref}}$.

- c: Total conversion factor from energy flux incident at the telescope entrance to detected number of photo-electrons. [e$^-$/s per W/m^2/μm]

  $c = \epsilon\,\Delta\lambda\,A/E_\gamma$.

- T: Detector exposure time for one exposure (DIT). [s]

- n_{exp}: Number of exposures (NDIT).

- e: Encircled energy or fraction of PSF in the S/N reference area.

  For a point source this value is looked up in Table 4, 5 or 6 as appropriate for the chosen AO mode, using R_{ref} and λ_{ref} as input. For an extended source this parameter is not needed.

- N_{obj}: Number of detected electrons from object in the S/N reference area per exposure. [e$^-$]

  For a point source: $N_{\mathrm{obj}} = \hat{F}_{\mathrm{obj}}\,e\,c\,T$.
  For an extended source: $N_{\mathrm{obj}} = \hat{F}_{\mathrm{obj}}\,\Omega\,c\,T$.

- F_{sky}: Background surface brightness. [W/m^2/μm/arcsec^2]

  The background model is described in detail in Section 3.

- N_{sky}: Number of detected electrons from the background in the S/N reference area per exposure. [e$^-$]

  $N_{\mathrm{sky}} = F_{\mathrm{sky}}\,\Omega\,c\,T$.

- N_{pix}: Number of detector pixel over which the light from the S/N reference area is spread.

  $N_{\mathrm{pix}} = 2\,N_{\mathrm{spec}}$, where the factor 2 comes from the integration over wavelength.

- d: Detector dark current. [e$^-$/s/pixel]

  Set to 2, 4 and 2000 e$^-$ per hour for the optical, near-IR and mid-IR wavelength regions, respectively. I.e. $d = 0.00056$, 0.0011 and 0.56 e$^-$/s for these regions.

- r: Detector read-out noise. [e$^-$/pixel]

  Set to 2, 3 and 200 e$^-$ for the optical, near-IR and mid-IR wavelength regions, respectively.

- S/N: Signal-to-noise ratio per resolution element.

$$S/N = \frac{\sqrt{n_{\mathrm{exp}}}\,N_{\mathrm{obj}}}{\sqrt{N_{\mathrm{obj}} + N_{\mathrm{sky}} + N_{\mathrm{pix}}\,r^2 + N_{\mathrm{pix}}\,d\,T}}.$$

3. Explanations

3.1. The target

The target's flux is specified by giving its magnitude in any one of the allowed bands (U to Q), and its flux distribution. The latter is integrated over the chosen band and then normalised to the specified magnitude. The zeropoints of the magnitude scale may be either Vega or AB (cf. Table 1). Together, the input magnitude and the flux distribution determine the object flux at the observing wavelength, λ_{ref} (which may also lie in the range U to Q). Normally, ESO ETCs offer the Pickles library of stellar spectra to select a stellar flux distribution from. However, these spectra do not extend beyond the K-band. For longer wavelengths the ETC offers the MARCS model spectra supplied by N. Ryde of Uppsala Observatory. See http://marcs.astro.uu.se/ for details regarding the models. At present, the complexities of the models are a little daunting for non-specialists. To help with the choice of parameters a useful 'standard' subset of just a ∼dozen or so models will soon be offered by the ETC. Alternatively, the target's flux at λ_{ref} may be specified directly in mJy.

The source geometry can be chosen to be a point source or an extended source. In the latter case the target magnitude is assumed to be a surface brightness in mag/arcsec^2.

3.2. The S/N reference area

The user has to specify the radius of a 'S/N reference area' in mas ($R_{\rm ref}$). This is the area on the sky over which the photons for the S/N calculation (both object and sky) are collected. So for an extended source (and the sky) the number of object (sky) photons is simply given by multiplying the target's (sky's) surface brightness by $\pi R_{\rm ref}^2$. For a point source, on the other hand, only some fraction of the object's flux will fall within the S/N reference area. For a given area this fraction depends on the PSF and hence on the chosen AO mode: Seeing limited (i.e. no AO), Ground Layer AO, or Laser Tomography AO. For a given AO mode and observing band the fractional energy encircled by the S/N reference area is obtained from a look-up table. The tables for the various AO modes are reproduced in Tables 4, 5 and 6, and are presented graphically in Figs. 1, 2 and 3. The values in these tables were measured from simulated PSFs provided by M. Le Louarn. All PSF simulations assume a DIMM seeing of FWHM = 0.8 arcsec at 0.5 μm and a 42 m telescope. Note that we do not have simulations for an 8.2 or 30 m telescope, which can also be chosen by the user. Hence, making these choices for the diameter affects only the photon collecting area, but *not* the PSF. Similarly, the PSFs do not change when selecting different sites or airmasses. Finally, we note that the E-ELT is likely to offer AO modes other than those listed above, such as Multi-Conjugate AO or Extreme AO. Currently, we lack appropriate PSF simulations to properly include these AO modes in the ETC. However, in the case of MCAO it is probably not too unreasonable to assume similar performance as for LTAO.

The user also has to specify the number of individual spectra over which the light collected in the S/N reference area is distributed, i.e. the number of pixels perpendicular to the dispersion direction over which the light at a given wavelength is spread. Often this is identical to the number of spatial elements (spaxel) in the S/N reference area. In that case the size of a spaxel on the sky is simply given by: $\Omega_p = \pi R_{\rm ref}^2 / N_{\rm spec}$ (in mas^2 per spaxel).

The final S/N is calculated per spectral resolution element, i.e. the object's (and the sky's) light is integrated over $\Delta\lambda = \lambda_{\rm ref}/R$, where R is the spectral resolution. The ETC assumes that $\Delta\lambda$ is sampled by two pixels.

To summarise: given an object's magnitude (point source) or surface brightness (extended source) the size of the S/N reference area determines either an 'aperture correction' for a point source or the area over which an extended source's light is collected. It also determines the number of sky photons. Note that it does not make sense to select a value for $R_{\rm ref}$ that is smaller than the radius of the PSF's diffraction limited core (DFC) in the band of observation. That is why the DFC for each band is marked in the ETC's drop-down list of $R_{\rm ref}$ values. $N_{\rm spec}$ determines the number of detector pixels over which the light collected from the S/N reference area is spread: $N_{\rm pix} = 2N_{\rm spec}$, where the factor 2 comes from the integration over

wavelength. Hence, $N_{\rm spec}$ determines the readout noise and dark current.

Usually, in instrument-specific ETCs, the parameters $R_{\rm ref}$ and $N_{\rm spec}$ are fixed by the instrument and/or the ETC developer. Giving the user control over these parameters provides a large amount of flexibility, so that different instrumental characteristics can be dealt with. The following is a list of examples of how to choose $R_{\rm ref}$ and $N_{\rm spec}$ in various situations.

- IFU:
  Here Ω_p is the size of a spaxel on the sky in mas^2, as defined above, and we assume that each spaxel produces exactly one spectrum on the detector. Ω_p should be taken from the specifications of the particular instrument you are considering.

  - point source:
    Choose $R_{\rm ref}$ = size of the PSF in the band you are observing in.
    $N_{\rm spec} = \pi R_{\rm ref}^2/\Omega_p$.
  - extended source, S/N in a single spectrum:
    $R_{\rm ref} = \sqrt{\Omega_p/\pi}$.
    $N_{\rm spec} = 1$.
  - extended source, total object S/N:
    $R_{\rm ref}$ = size of object.
    $N_{\rm spec} = \pi R_{\rm ref}^2/\Omega_p$.

- CODEX, point source:
  $R_{\rm ref}$ = size of entrance aperture (something large so that flux loss is small).
  $N_{\rm spec} = 280$.
  The number for $N_{\rm spec}$ was taken from a preliminary design of CODEX. In this design the object's spectrum is spread over 70 pixel at a given wavelength. This number has to be multiplied by 2 because there will be two cameras (at a given wavelength). Furthermore, CODEX will sample a resolution element with 4 pixel, not with 2 pixel as the ETC assumes. Hence another factor of 2 is applied to correct for this.

- Classical long-slit spectrograph:
  In this case the S/N reference area is quasi-rectangular, contrary to the ETC's assumption of a circular S/N reference area. However, for an extended source the ETC can easily be 'tricked' into doing the correct thing. Here w is the slit width and Ω_p is the linear size of a pixel on the sky, both in mas.

  - extended source, S/N in a single spectrum:
    $R_{\rm ref} = \sqrt{w\,\Omega_p/\pi}$.
    $N_{\rm spec} = 1$.

- extended source, total object S/N:
  $R_{\mathrm{ref}} = \sqrt{w \, (\text{size of object})/\pi}$.
  $N_{\mathrm{spec}} = (\text{size of object})/\Omega_p$.

- point source:
  Unlike the above, this case cannot be represented exactly. In the previous case (long slit + extended source) the geometry of the S/N reference area is irrelevant but in the present case it is not, and one is left with two imperfect alternatives for R_{ref}:

  1. $R_{\mathrm{ref}} = \sqrt{w \, (\text{size of PSF})/\pi}$. With this choice the ETC will calculate the correct number of sky photons but most likely it will get the aperture correction wrong, and therefore it will use the wrong number of object photons.

  2. One chooses R_{ref} such that the aperture correction equals the expected or intended slit loss. In this case the ETC will use the correct number of object photons, however, it will likely estimate the wrong number of sky photons.

  The only solution is to run both of the above options with the 'Detailed S/N Info' box checked in order to obtain all the relevant numbers, and then to manually correct the number of either the object or sky photons to derive the correct result.

3.3. The background model

The ETC models the sky (or rather background) brightness and its dependence on wavelength in the following way:

$$F_{\mathrm{sky}}(\lambda) = \mathrm{cont}(\lambda) + \mathrm{em.lines}(\lambda) + \mathrm{atm}(\lambda) + \mathrm{tel}(\lambda), \tag{1}$$

i.e. as the sum of a 'continuum', 'emission lines', thermal atmospheric emission and thermal emission from the telescope (and instrument).

In the blue-optical the sky brightness is dominated by the 'continuum' which has contributions from a number of sources, chiefly: diffuse galactic emission, zodiacal light and moonlight scattered by the atmosphere. Hence, in practice the sky brightness at a given wavelength and at a given position in the sky depends on a number of parameters, including the position's location with respect to the galaxy, ecliptic and moon, the moon phase, the phase of the solar cycle, the season, the observatory's geomagnetic latitude and airmass. Compared to the darkest possible sky most of these systematic effects increase the sky brightness by up to several tenths of a magnitude. The moon has the largest effect – up to several magnitudes in the blue. In addition, even when all known systematic effects are accounted for, the sky brightness still fluctuates by ∼0.2 mag on timescales of minutes, hours and nights. Unfortunately, even if we concentrate only on the most prominent effect (the moon) and ignore all

others, an accurate model of the sky brightness still requires a complexity that is currently beyond most ETCs.

The ETC adopts a value for the 'continuum' that remains constant in each band. For the $UBVRI$ bands these continuum values correspond to the broadband brightnesses as given by the 'standard' ESO ETC sky brightness table for a moon phase of 3 days from new moon. Any dependencies on the site and airmass are ignored.

In the near-IR the sky brightness is dominated by the 'emission line' component (mostly OH airglow) and hence the 'standard' broadband sky brightnesses are inappropriate for the 'continuum'. Instead the ETC uses the 'continuum' values measured with ISAAC by Cuby et al. (2000, The Messenger, 101, 2) in the J and H bands. (Note: these values are uncertain by a factor of a few, cf. Maihara et al., 1993, PASP, 105, 940; Ellis & Bland-Hawthorn, 2008, MNRAS, 386, 47.) The H-band value is also used in the K-band, beyond which the 'continuum' is irrelevant. All 'continuum' values are summarised in Table 3.

Although the sky brightness in JHK is independent of the moon's phase it is nevertheless quite uncertain. The reason is that the airglow is known to vary systematically as a function of season and time of night, as well as randomly on shorter timescales and as a function of position on the sky, by several tenths of a mag. Note that any dependencies of the strength of the OH airglow on the site and airmass are again ignored.

From the second half of the K-band onwards the background is dominated by the thermal emission from the atmosphere and the telescope. The atmospheric emission was calculated by A. Smette using the HITRAN molecular database and assuming a tropical atmospheric profile. Molecules included are: H_2O, CO, CO_2, CH_4, O_2, O_3 and N_2O. These calculations were performed for four different values of airmass and for two different sites: (i) a Paranal-like site and (ii) a High and Dry site at an altitude of 5000 m. The assumed characteristics of each site are listed in Table 2.

The emission from the telescope is modeled as a grey body, i.e. as a black body multiplied by a constant emissivity of 0.14 (corresponding to 5 aluminium-coated mirrors) and a temperature equal to the selected site's ambient temperature.

The background model is shown in Figs. 4–8 at a resolution of $R = 1000$. The faint grey line in each of the figures shows a similar model from the Gemini ETC for Mauna Kea. The comparison highlights some of the uncertainties. The differences in the blue-optical (Fig. 4) are mainly due to different assumptions regarding the amount of the moonlight, although the Gemini model also rises quite steeply towards the red which is difficult to explain with just the moon. In the near-IR the model 'continua' are also different in shape (Fig. 5). The Gemini model assumes that the 'continuum' is due to zodiacal light which is modeled by a

black body with a temperature of 5800 K and which is subject to atmospheric extinction. However, the normalisation is far too high for zodiacal light (by a factor of ~ 70) and must be arbitrarily cut off near 0.9 μm in order to avoid producing far too much background light in the optical. The agreement in the OH lines, on the the other hand, is reasonable, and the apparent differences are mainly due to resolution. Note that the Gemini model does not include a telescope component. Hence the rise in the the second half of the K-band is solely due to the atmosphere. By comparing Figs. 5 and 6 we can see that the model atmosphere for Mauna Kea lies in-between those for the Paranal-like site and the High and Dry site, as it should.

In addition to its emission the atmosphere also affects the S/N calculation by not being completely transparent to photons from astronomical sources. Atmospheric extinction is due to (at least) two different processes: molecular absorption and scattering by molecules and aerosols. The absorption is calculated by the same atmospheric model already described above, again for all combinations of airmass and site. Since scattering is only effective in the blue-optical, where molecular absorption is almost absent, we use a 'standard' Paranal blue-optical extinction curve to represent the effect of scattering. The combined, total atmospheric transmission is hence given by $\xi(\lambda) = \xi_{\mathrm{abs}}(\lambda)\,\xi_{\mathrm{sc}}(\lambda) = \xi_{\mathrm{abs}}(\lambda)\,10^{-0.4\,\chi\,k(\lambda)}$, where $\xi_{\mathrm{abs}}(\lambda)$ is given by the atmospheric model and $k(\lambda)$ is the extinction curve (= 0 for $\lambda > 0.7$ μm). For the High and Dry site the Paranal extinction curve is multiplied by 0.6 (Giraud et al., 2006, astro-ph/0611262). The combined, total atmospheric transmission is shown in Figs. 9–14.

Table 1.   Photometric zeropoints

Band	Central wavelength [μm]	$Z_{\text{Vega}} = -\log F_0$ [W/m^2/μm]	$Z_{\text{AB}} = -\log F_0$ [W/m^2/μm]
U	0.36	7.38	7.09
B	0.44	7.18	7.25
V	0.55	7.44	7.44
R	0.64	7.64	7.58
I	0.79	7.91	7.77
J	1.25	8.51	8.14
H	1.65	8.94	8.39
K	2.16	9.40	8.64
L	3.50	10.32	9.04
M	4.80	10.69	9.32
N	10.20	11.91	10.00
Q	21.00	13.17	10.57

Table 2.   Assumed site characteristics

Site	Altitude [m]	Temperature [K]	Pressure [mb]	PWV [mm]
Paranal	2600	285	743	2.3
High and Dry	5000	270	540	0.5

Table 3.   Values for the 'continuum' component of the background model

Band	'Continuum' brightness [γ/s/μm/m^2/arcsec^2]	[mag/arcsec^2]	Comment
U	190	21.5	Standard ESO ETC sky brightness table
B	150	22.4	for 3 days from new moon
V	210	21.7	
R	340	20.8	
I	500	19.9	
J	1200	18.0	Cuby et al., 2000, Messenger, 101, 2
H	2300	16.5	Cuby et al., 2000, Messenger, 101, 2
K	2300	15.7	

Note. — The 'continuum' values are assumed to independent of the site and airmass. Beyond the K-band the 'continuum' component of the background model is irrelevant.

Table 4. Encircled energies for seeing limited case (no AO)

$R_{\rm ref}$ [mas]	Percentage of energy enclosed in the S/N reference area of radius $R_{\rm ref}$											
	U	B	V	R	I	J	H	K	L	M	N	Q
2.2	0.00229	0.00263	0.00282	0.00325	0.00380	0.00480	0.00474	0.00646	0.0142	0.0367	0.160	0.0867
2.6	0.00322	0.00362	0.00396	0.00460	0.00529	0.00663	0.00664	0.00908	0.0201	0.0512	0.223	0.121
3.3	0.00519	0.00582	0.00640	0.00737	0.00857	0.0107	0.0110	0.0146	0.0331	0.0824	0.359	0.195
4.2	0.00843	0.00934	0.0104	0.0119	0.0140	0.0174	0.0180	0.0236	0.0531	0.134	0.582	0.316
5.0	0.0119	0.0132	0.0147	0.0169	0.0199	0.0245	0.0260	0.0348	0.0758	0.188	0.825	0.448
5.4	0.0139	0.0154	0.0171	0.0198	0.0233	0.0283	0.0306	0.0410	0.0881	0.219	0.962	0.523
7.5	0.0268	0.0295	0.0328	0.0384	0.0451	0.0540	0.0619	0.0828	0.167	0.405	1.83	1.01
9.9	0.0468	0.0512	0.0572	0.0670	0.0775	0.0950	0.114	0.150	0.289	0.683	3.10	1.76
10.0	0.0478	0.0523	0.0584	0.0685	0.0792	0.0968	0.116	0.153	0.290	0.700	3.14	1.79
13.0	0.0809	0.0886	0.0982	0.115	0.133	0.167	0.202	0.265	0.488	1.13	4.98	3.03
15.0	0.108	0.118	0.131	0.152	0.177	0.224	0.271	0.355	0.634	1.47	6.30	4.02
20.0	0.192	0.209	0.234	0.270	0.316	0.397	0.493	0.623	1.10	2.38	10.3	6.84
21.0	0.212	0.231	0.258	0.298	0.348	0.437	0.544	0.683	1.20	2.56	11.4	7.42
29.0	0.403	0.441	0.493	0.567	0.660	0.826	1.02	1.27	2.23	4.27	18.8	12.6
50.0	1.19	1.30	1.46	1.67	1.94	2.42	2.93	3.76	6.44	9.94	30.3	32.0
63.0	1.88	2.06	2.31	2.64	3.06	3.79	4.59	5.86	9.55	14.3	33.7	41.2
100.0	4.66	5.08	5.68	6.47	7.46	9.13	11.0	13.7	20.2	27.0	47.8	55.1
120.0	6.63	7.21	8.04	9.13	10.5	12.8	15.3	18.6	26.8	33.8	53.5	57.0
150.0	10.1	11.0	12.2	13.7	15.7	18.9	22.3	26.7	35.8	43.4	59.9	62.3
200.0	17.1	18.4	20.3	22.7	25.6	30.1	34.7	40.1	49.8	56.4	68.7	74.7
300.0	33.5	35.6	38.5	42.0	46.1	51.8	56.8	61.9	69.5	73.7	80.4	81.2
400.0	50.0	52.4	55.5	59.1	63.0	68.0	71.9	75.6	80.5	83.0	86.4	86.5
500.0	64.0	66.1	68.8	71.8	74.8	78.5	81.2	83.6	86.7	88.2	90.0	89.7
800.0	88.0	88.3	88.9	89.8	90.7	91.8	92.6	93.3	94.2	94.6	94.9	94.1
1000.0	94.5	93.9	93.8	94.0	94.3	94.8	95.2	95.6	96.1	96.3	96.3	95.6

Note. — Measured from PSF simulations for a $D = 42$ m telescope. DIMM seeing $= 0.8$ arcsec at 0.5 μm. In each band the red number marks the size of the diffraction limited core. Hence the numbers above the red values are not overly useful or even meaningful.

Table 5.   Encircled energies for GLAO

$R_{\rm ref}$					Percentage of energy enclosed in the S/N reference area of radius $R_{\rm ref}$							
[mas]	U	B	V	R	I	J	H	K	L	M	N	Q
2.2	0.00278	0.00319	0.00376	0.00446	0.00594	0.00957	0.0136	0.0310	0.234	0.449	0.303	0.104
2.6	0.00390	0.00446	0.00530	0.00635	0.00836	0.0131	0.0189	0.0426	0.325	0.627	0.424	0.145
3.3	0.00631	0.00716	0.00844	0.0103	0.0132	0.0211	0.0306	0.0674	0.497	1.000	0.683	0.234
4.2	0.0103	0.0115	0.0135	0.0168	0.0217	0.0338	0.0495	0.108	0.761	1.56	1.11	0.378
5.0	0.0145	0.0163	0.0190	0.0236	0.0303	0.0467	0.0695	0.150	1.03	2.13	1.57	0.536
5.4	0.0169	0.0191	0.0222	0.0275	0.0353	0.0546	0.0805	0.173	1.16	2.45	1.83	0.626
7.5	0.0324	0.0365	0.0431	0.0522	0.0677	0.102	0.158	0.318	2.08	4.17	3.52	1.21
9.9	0.0566	0.0629	0.0743	0.0909	0.117	0.175	0.276	0.524	3.18	6.78	5.88	2.10
10.0	0.0577	0.0642	0.0758	0.0928	0.119	0.179	0.280	0.539	3.20	6.93	5.94	2.15
13.0	0.0975	0.109	0.128	0.156	0.198	0.297	0.471	0.866	4.29	10.4	9.31	3.63
15.0	0.130	0.145	0.170	0.209	0.263	0.393	0.624	1.14	4.97	12.1	11.8	4.81
20.0	0.230	0.259	0.301	0.370	0.466	0.695	1.08	1.98	6.35	15.7	19.3	8.14
21.0	0.254	0.286	0.333	0.408	0.514	0.766	1.19	2.17	6.64	16.1	21.0	8.79
29.0	0.483	0.543	0.635	0.772	0.970	1.44	2.15	3.83	10.2	18.8	34.2	15.1
50.0	1.43	1.60	1.87	2.26	2.84	4.09	5.94	9.41	20.1	31.7	51.0	38.0
63.0	2.25	2.52	2.94	3.55	4.45	6.30	9.00	13.7	25.6	37.4	52.9	48.7
100.0	5.55	6.19	7.16	8.54	10.5	14.4	19.5	26.7	39.7	50.4	68.4	63.8
120.0	7.85	8.74	10.1	11.9	14.6	19.5	25.5	33.5	46.3	55.7	72.9	65.0
150.0	11.9	13.2	15.1	17.7	21.2	27.4	34.3	42.7	55.0	62.6	75.8	69.6
200.0	19.8	21.8	24.6	28.2	32.8	40.2	47.4	55.1	65.3	71.5	80.8	82.6
300.0	37.7	40.5	44.2	48.7	53.7	60.5	66.0	71.2	77.9	81.5	86.5	86.3
400.0	54.5	57.2	60.7	64.7	68.7	73.6	77.2	80.5	84.6	87.0	90.2	90.0
500.0	67.9	70.0	72.7	75.6	78.4	81.7	84.1	86.1	88.7	90.3	92.2	92.0
800.0	89.3	89.4	89.9	90.6	91.4	92.3	93.1	93.7	94.5	94.9	95.5	95.0
1000.0	95.0	94.4	94.2	94.3	94.6	95.0	95.4	95.8	96.2	96.4	96.6	96.1

Note. — Measured from PSF simulations for a $D = 42$ m telescope. In each band the red number marks the size of the diffraction limited core. Hence the numbers above the red values are not overly useful or even meaningful.

Table 6.   Encircled energies for LTAO

$R_{\rm ref}$	Percentage of energy enclosed in the S/N reference area of radius $R_{\rm ref}$											
[mas]	U	B	V	R	I	J	H	K	L	M	N	Q
2.2	0.00400	0.00500	0.0160	0.161	0.973	3.08	4.39	4.49	2.77	1.67	0.394	0.111
2.6	0.00500	0.00700	0.0210	0.201	1.23	4.09	5.84	5.93	3.87	2.33	0.550	0.154
3.3	0.00900	0.0120	0.0310	0.265	1.63	6.06	8.79	8.82	6.06	3.76	0.886	0.249
4.2	0.0140	0.0190	0.0460	0.336	2.03	7.91	13.2	13.1	9.06	5.98	1.44	0.403
5.0	0.0200	0.0270	0.0610	0.400	2.29	9.40	15.9	17.9	12.0	8.11	2.04	0.571
5.4	0.0230	0.0310	0.0700	0.433	2.40	9.91	17.2	20.4	13.8	9.23	2.37	0.666
7.5	0.0450	0.0590	0.121	0.605	3.10	11.5	22.2	28.9	24.0	15.9	4.58	1.28
9.9	0.0780	0.102	0.193	0.787	3.78	13.5	24.1	35.4	36.0	25.4	7.67	2.24
10.0	0.0790	0.104	0.196	0.794	3.80	13.6	24.2	35.5	36.2	25.8	7.86	2.28
13.0	0.133	0.172	0.307	1.01	4.33	16.2	27.7	37.5	45.6	38.7	12.1	3.86
15.0	0.176	0.228	0.392	1.17	4.58	16.9	30.8	39.3	50.8	44.9	15.3	5.14
20.0	0.312	0.397	0.647	1.61	5.33	18.0	33.9	47.2	53.3	56.4	25.0	8.70
21.0	0.344	0.436	0.706	1.71	5.49	18.1	34.1	48.5	53.7	57.4	27.5	9.39
29.0	0.655	0.819	1.26	2.59	6.74	19.8	35.5	51.8	62.1	60.2	44.6	15.9
50.0	1.91	2.35	3.35	5.78	10.9	23.8	39.4	55.0	72.0	78.0	65.4	40.6
63.0	3.01	3.66	5.06	8.09	14.2	26.8	41.4	56.8	73.2	79.3	66.8	51.8
100.0	7.27	8.67	11.2	15.8	23.2	36.2	48.2	60.6	76.7	82.2	83.4	67.5
120.0	10.2	12.0	15.2	20.3	27.9	40.6	52.2	63.0	77.9	83.9	86.8	68.5
150.0	15.1	17.5	21.4	27.1	34.7	46.7	56.9	66.8	79.2	84.5	87.3	73.1
200.0	24.3	27.5	32.1	38.1	44.9	55.1	63.8	71.6	81.5	86.3	89.6	86.6
300.0	43.2	46.7	51.2	56.4	61.6	67.6	73.1	78.5	85.4	88.7	92.0	89.2
400.0	59.1	61.9	65.4	69.1	72.7	76.8	79.4	83.0	88.1	90.5	93.4	91.8
500.0	70.9	72.8	75.1	77.6	80.0	82.7	84.6	86.2	89.9	91.9	94.1	93.5
800.0	89.3	89.2	89.4	89.8	90.4	91.2	91.9	92.5	93.2	94.3	95.7	95.4
1000.0	94.7	93.7	93.3	93.3	93.4	93.7	94.1	94.4	94.9	95.2	96.3	96.1

Note. — Measured from PSF simulations for a $D = 42$ m telescope. In each band the red number marks the size of the diffraction limited core. Hence the numbers above the red values are not overly useful or even meaningful.
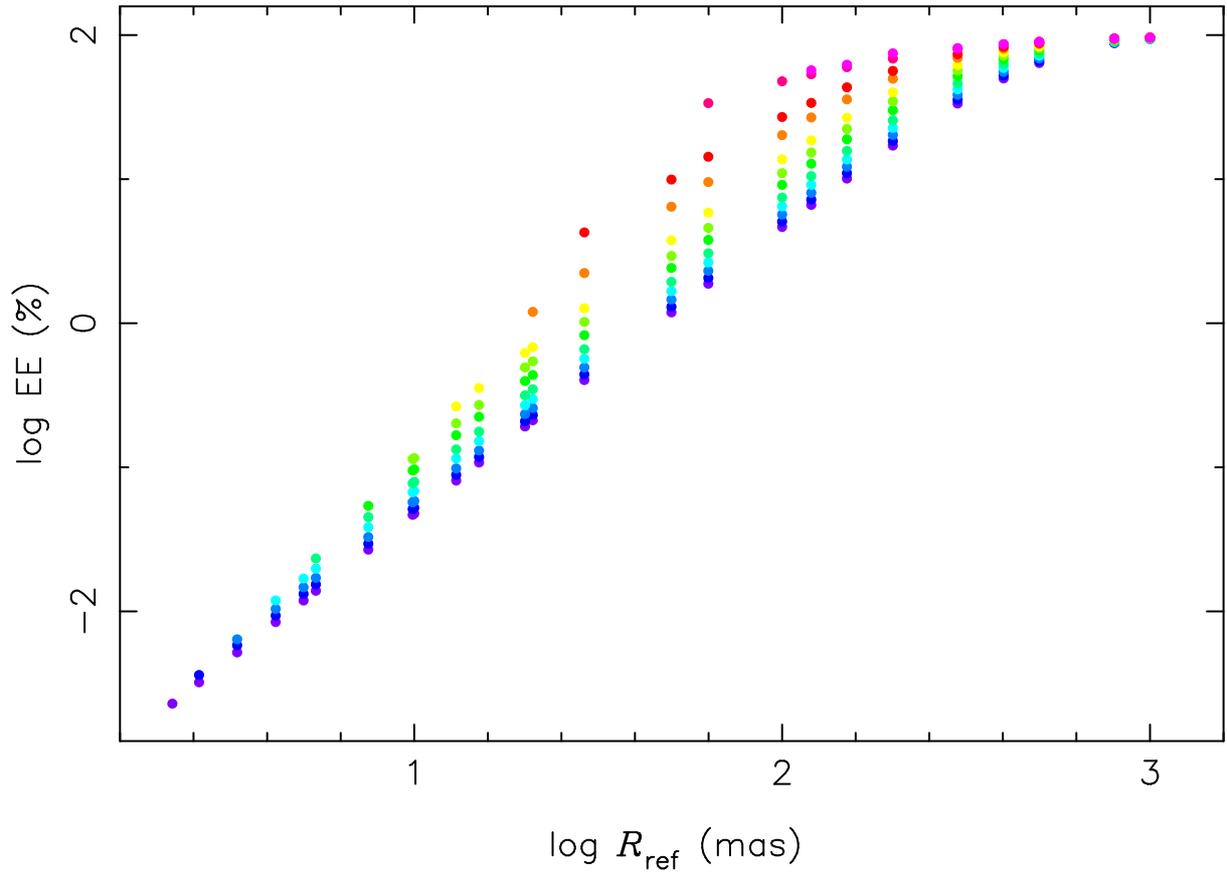
Fig. 1.— Encircled energy as a function of R_{ref} for no AO, i.e. a graphical representation of Table 4. Different bands are represented by differently coloured points. Values are only shown down to the band's DLC.
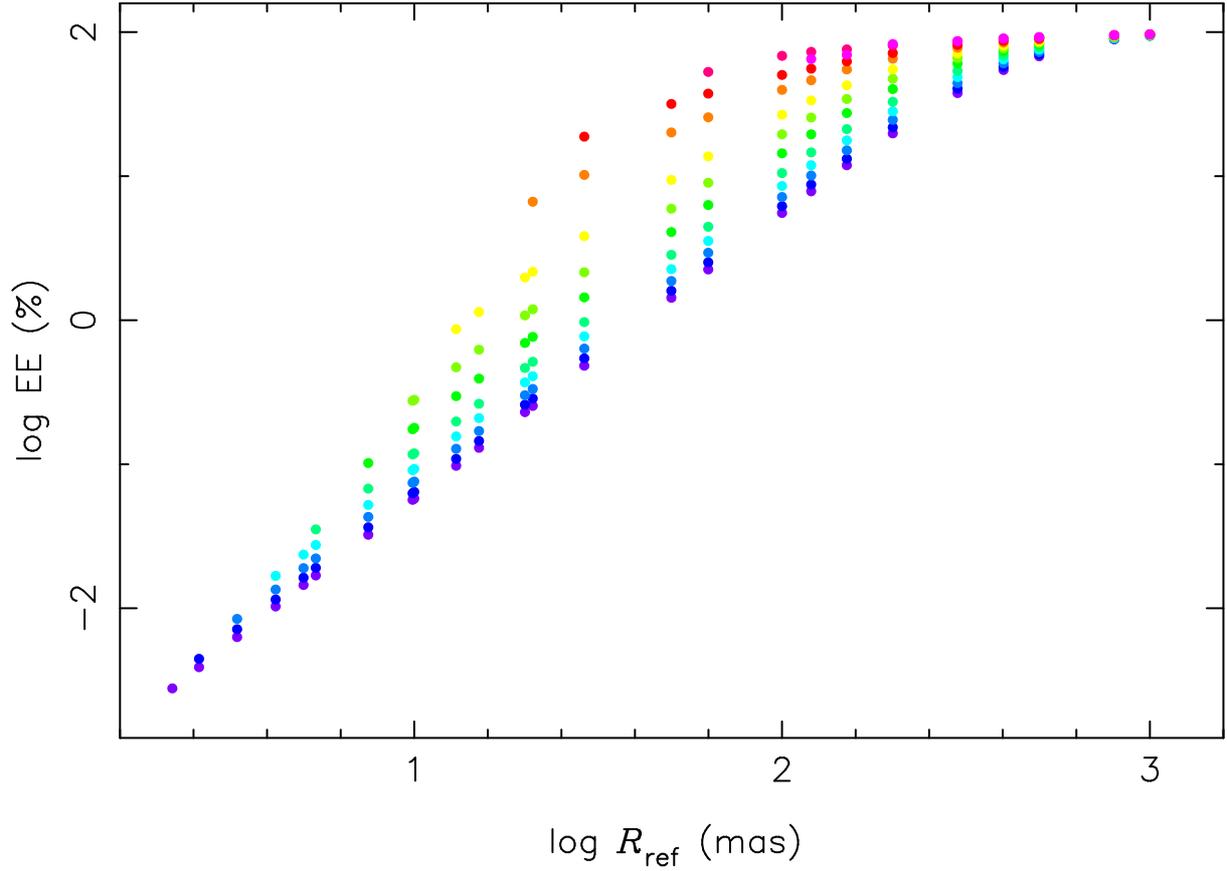
Fig. 2.— Encircled energy as a function of R_{ref} for GLAO, i.e. a graphical representation of Table 5. Different bands are represented by differently coloured points. Values are only shown down to the band's DLC.
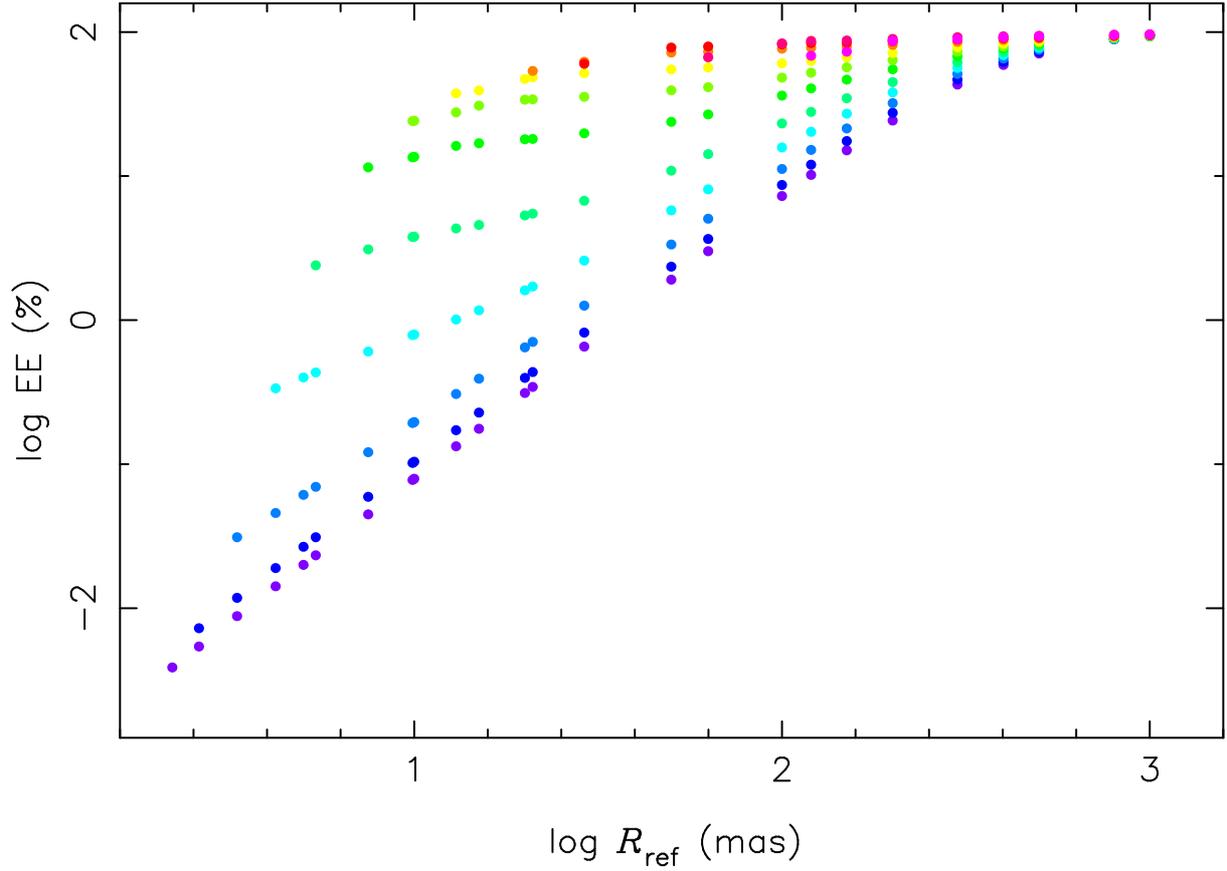
Fig. 3.— Encircled energy as a function of R_{ref} for LTAO, i.e. a graphical representation of Table 6. Different bands are represented by differently coloured points. Values are only shown down to the band's DLC.
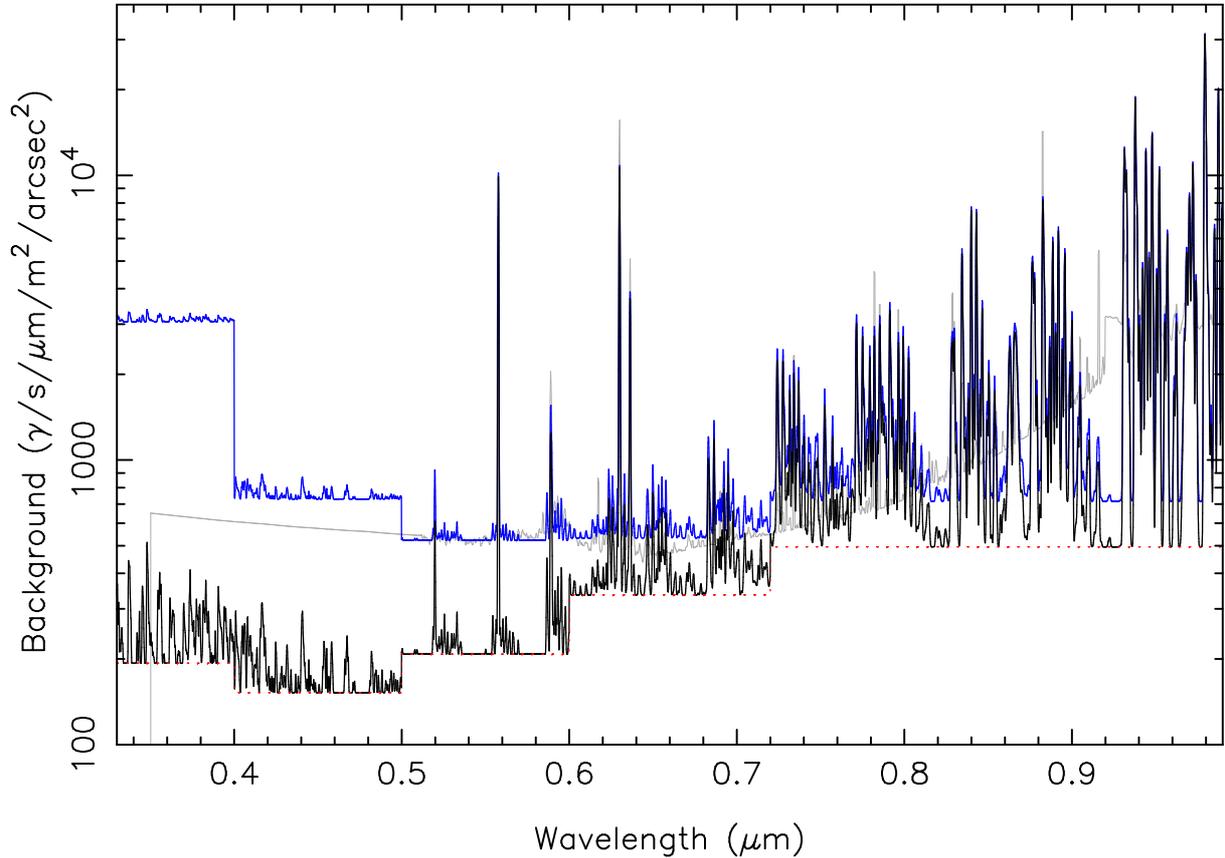
Fig. 4.— The black line shows the ETC's background model in the optical for 3 days from new moon and a resolution of $R = 1000$ (no site or airmass dependence). The dotted red line represents the 'continuum' (which is assumed to be constant in each band). For comparison, the faint grey line shows an optical background model from the Gemini ETC for Mauna Kea and for a moon phase of 7 days from new moon. To match this model's photon flux in the V-band with our model we need to select a moon phase of 10 days from new moon, which is shown as the blue line.
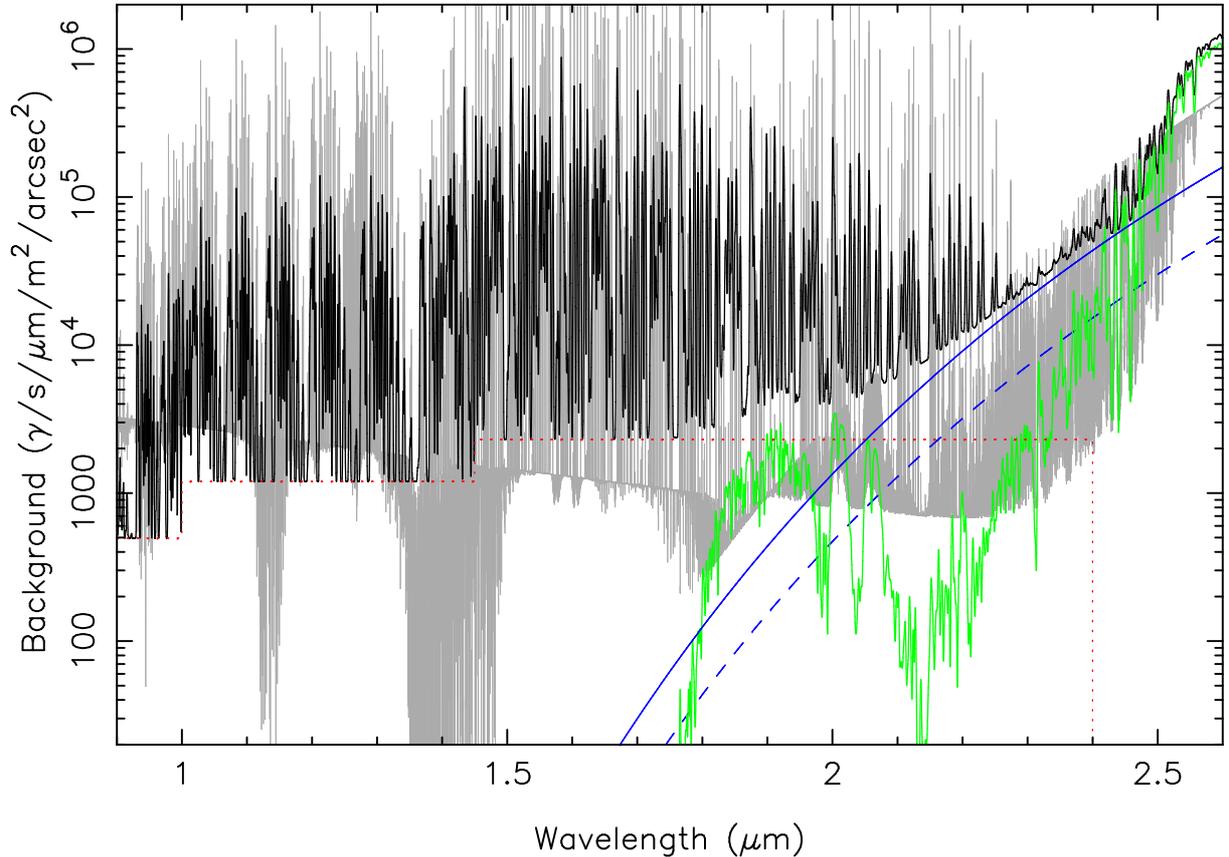
Fig. 5.— The black line shows the ETC's background model in the NIR for the Paranal-like site, 1 airmass and a resolution of $R = 1000$. The dotted red line represents the 'continuum' (which is assumed to be constant in each band but does not extend beyond the K-band). The blue line represents the background from the telescope (dashed line: same for a non-standard mirror coating) while the green line shows the thermal emission from the atmosphere. For comparison, the faint grey line shows a NIR background model from the Gemini ETC for Mauna Kea (at a much higher resolution).
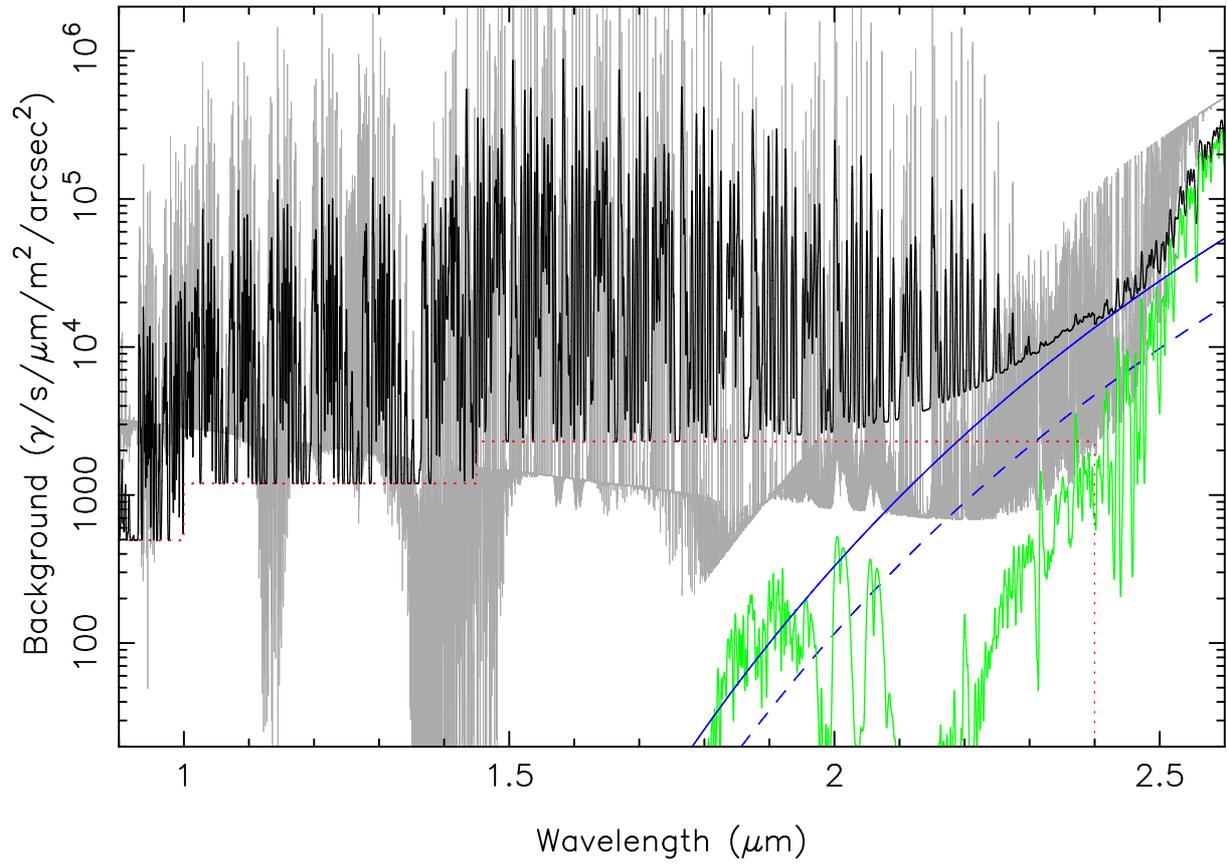
Fig. 6.— As Fig. 5 for the 'High and Dry' site.
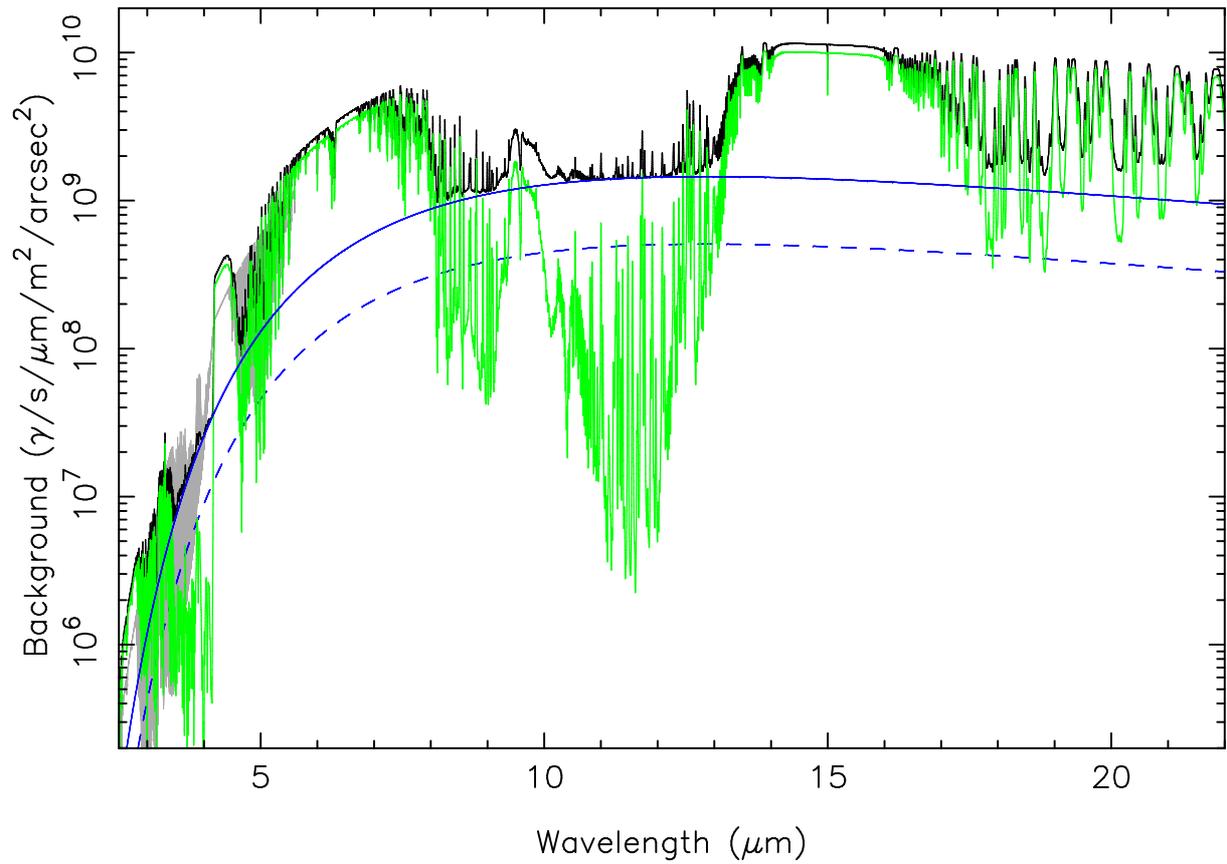
Fig. 7.— As Fig. 5 for the mid-IR. Note that the Gemini model (faint grey line) only extends to 5.6 μm.
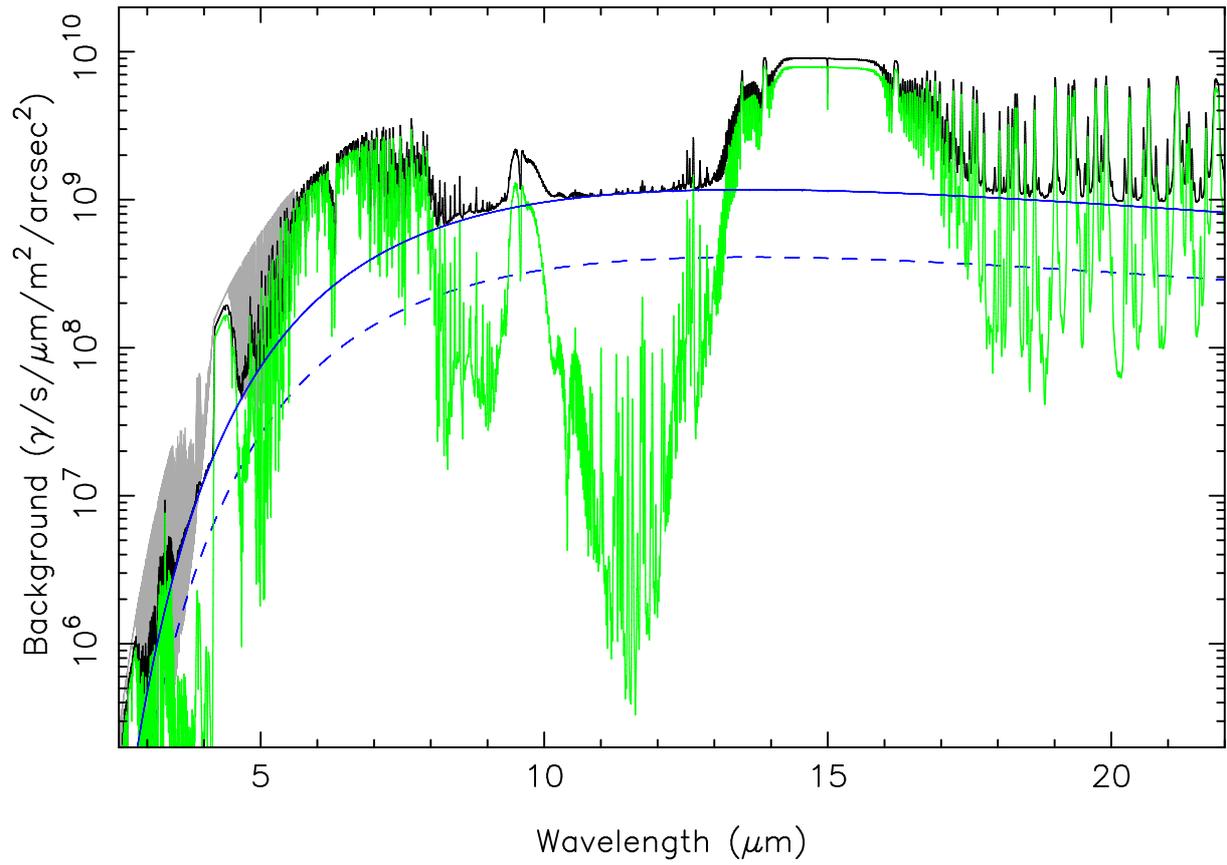
Fig. 8.— As Fig. 7 for the 'High and Dry' site.
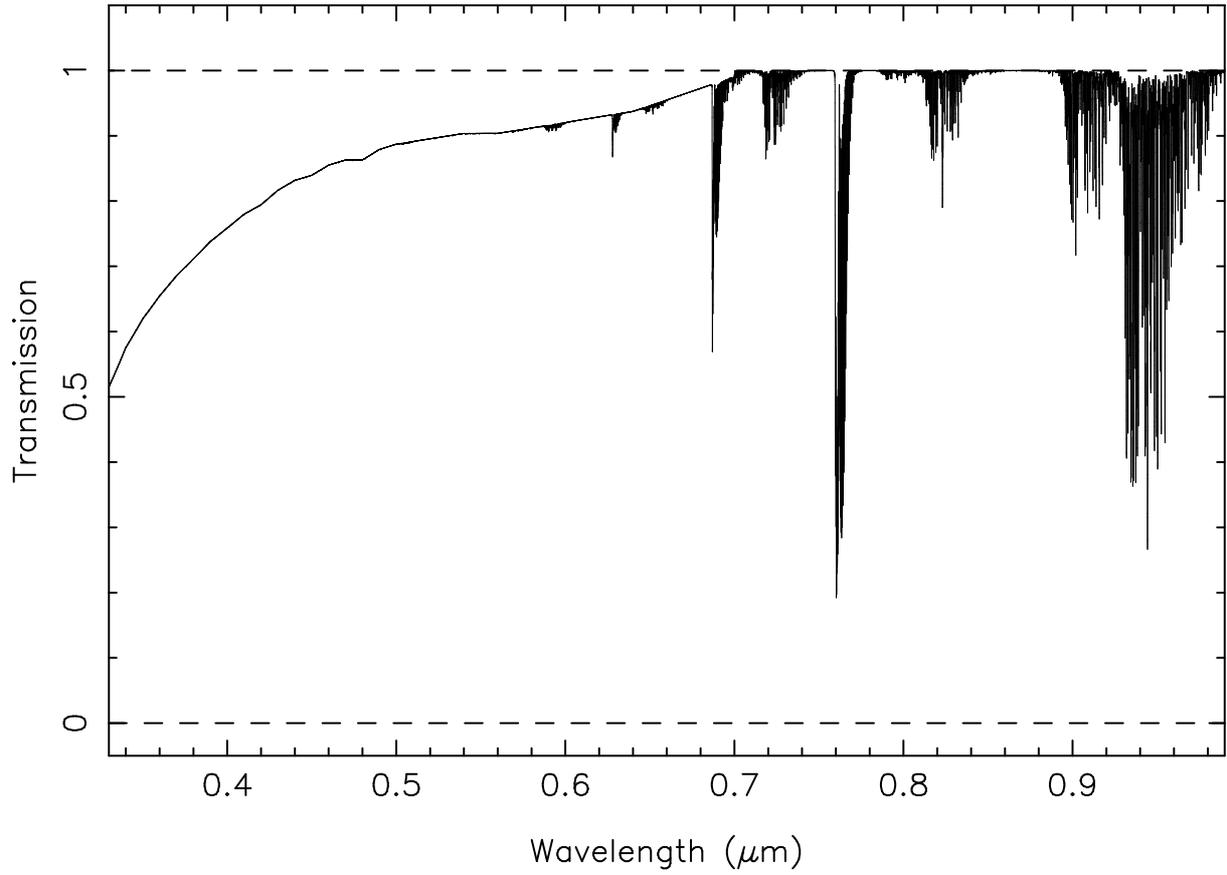
Fig. 9.— The atmospheric transmission (extinction) in the optical for the Paranal-like site, 1 airmass and a resolution of $R = 10000$.
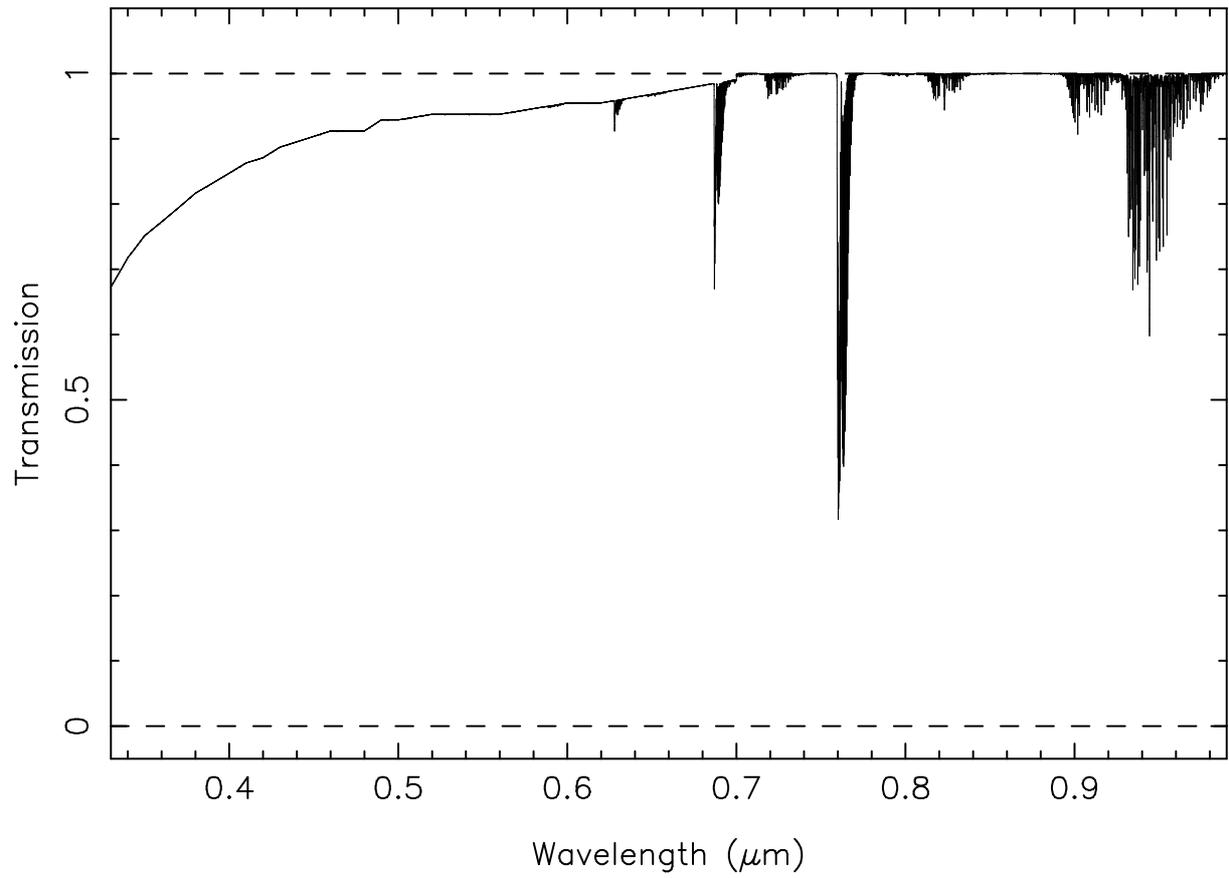
Fig. 10.— As Fig. 9 for the 'High and Dry' site.
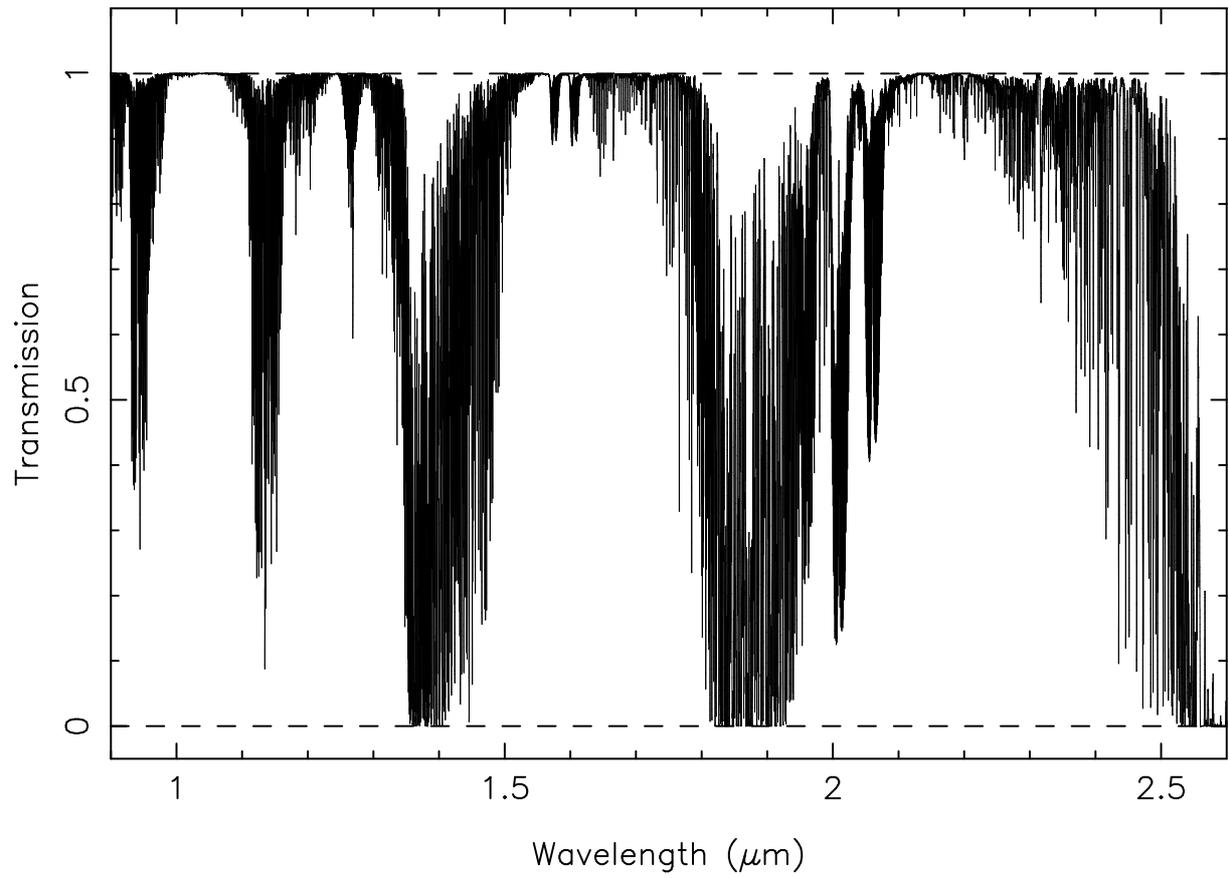
Fig. 11.— As Fig. 9 for the NIR.
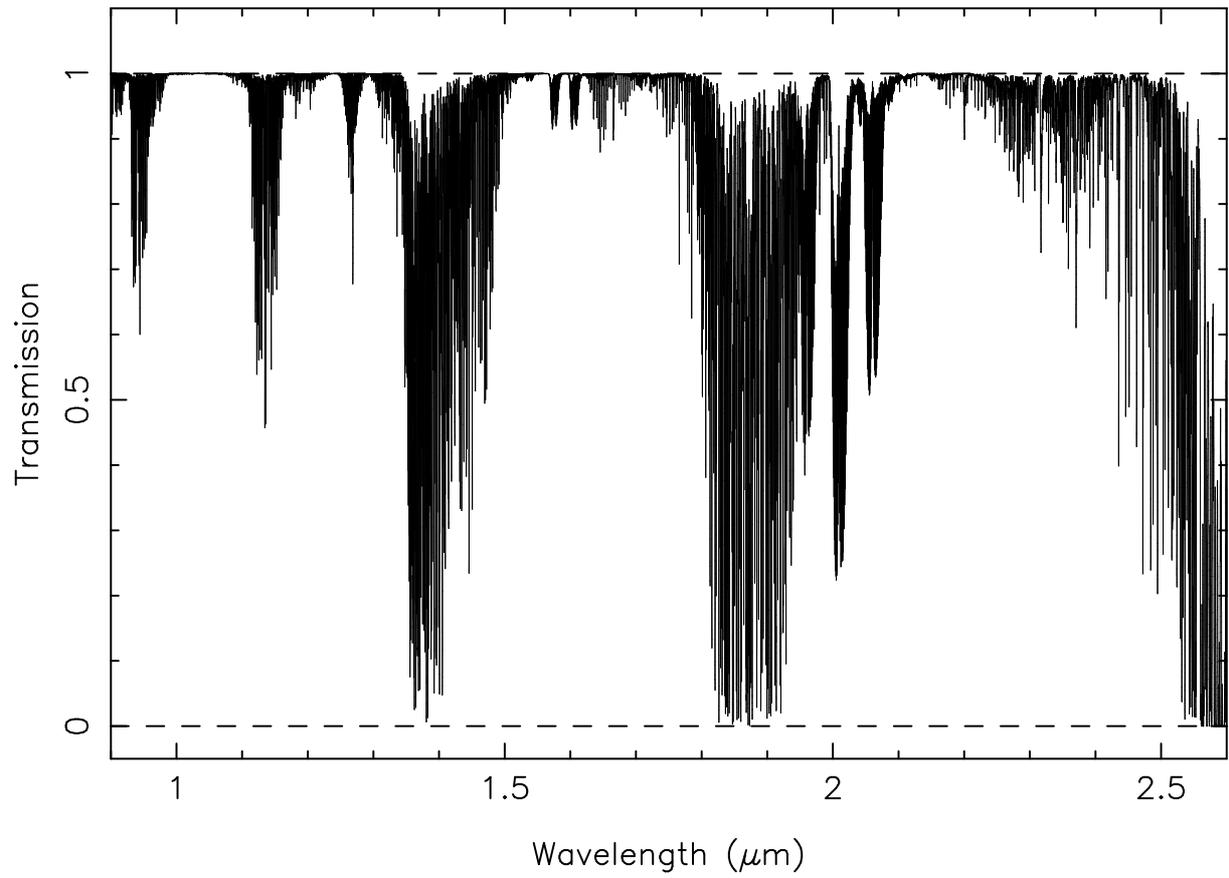
Fig. 12.— As Fig. 9 for the NIR and the 'High and Dry' site.
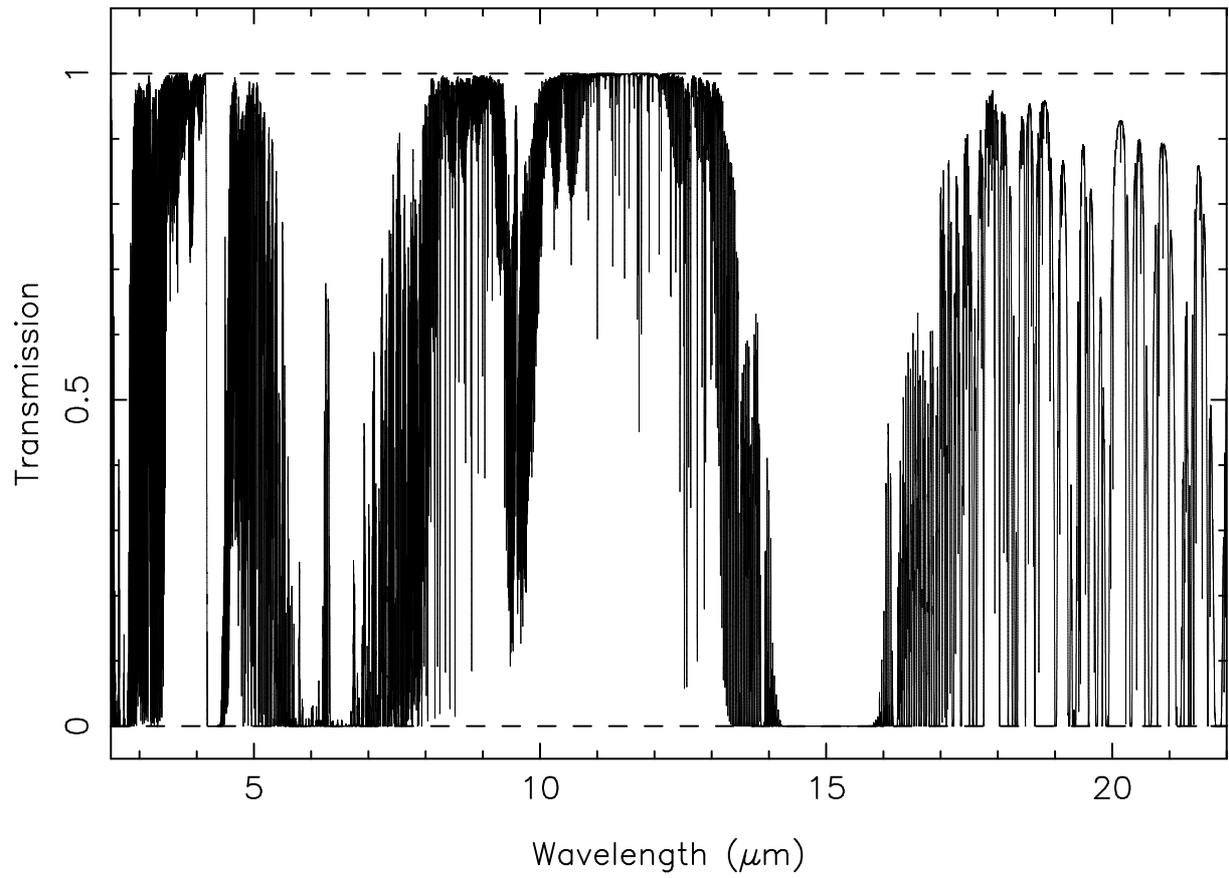
Fig. 13.— As Fig. 9 for the mid-IR.
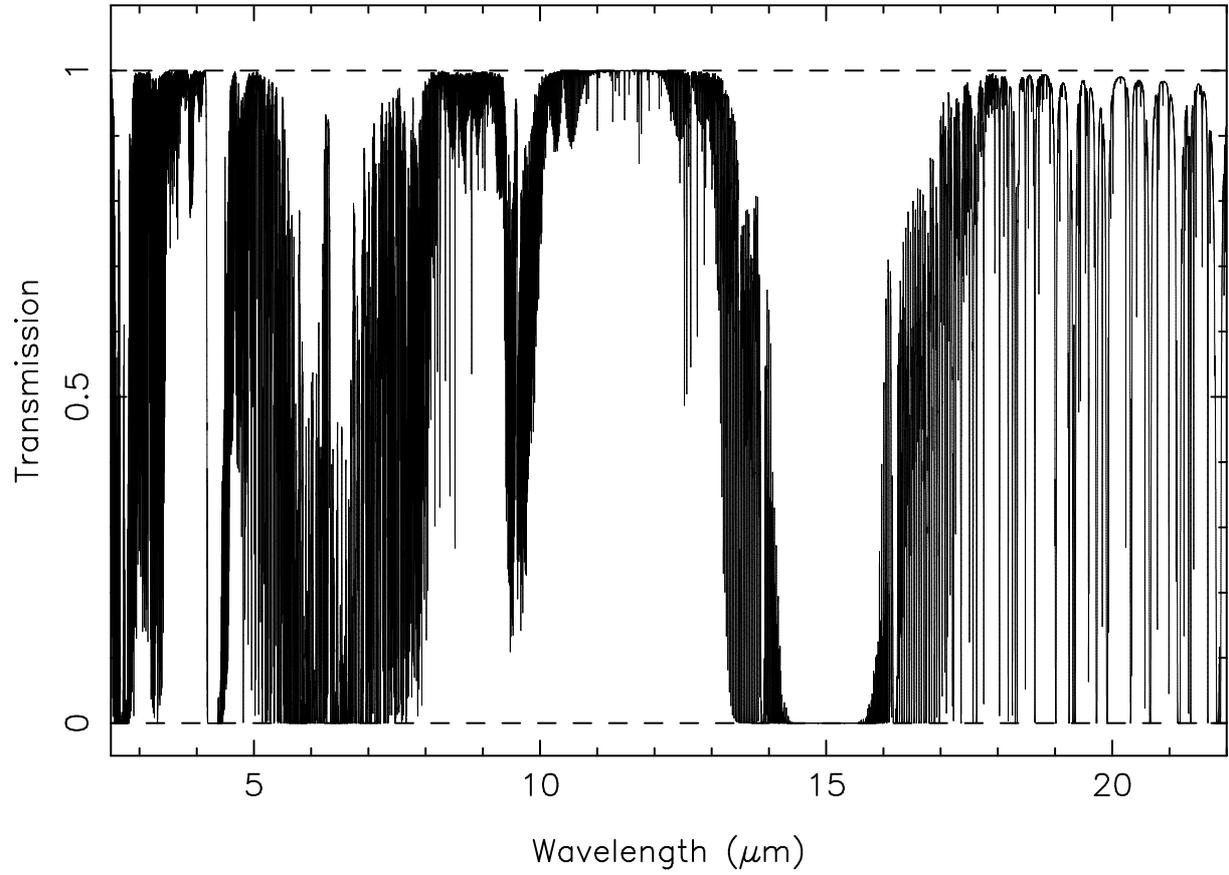
Fig. 14.— As Fig. 9 for the mid-IR and the 'High and Dry' site.