Correcting the chromatic and airmass dependent extinction for TIMMI2 spectra

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Abstract. We present a method to correct the chromatic and airmass dependent extinction for N-band spectra taken with the TIMMI2 instrument at the ESO / La Silla observatory. Usually, the target and calibrator star have to be observed at similar airmass in order to obtain reliable spectrophotometric fluxes. Our method allows to correct the atmospheric extinction and substantially improves the spectrophotometric flux calibration, when the standard stars were observed at a very different airmass than the targets. Hundreds of standard star measurements in several passbands (N1, N8.9, N10.4, N11.9) were used to derive mid-IR extinction coefficients. We demonstrate that applying our correction of the differential extinction to test data results in a spectrophotometric accuracy up to 2\% within the literature flux.

1 The influence of atmospheric extinction in the mid-IR

For spectroscopy the target stars and calibrators should generally be observed at a comparable airmass to avoid a varying extinction between the two objects. Different to near-IR observations, in the mid-IR a good calibrator at the same airmass is often difficult to find and the theoretical behaviour of the extinction with airmass and wavelength is not really known up to now. Some authors claim there would be no clear dependence and thus for photometry no airmass correction needs to be applied. However these authors used dozens of standard star observations, while we apply several hundred measurements.

In mid-IR spectroscopy the influence of extinction is more evident than for photometry. No good spectral flux calibrations are possible unless the target and calibrator star are observed close in time and very close in airmass (≤ 0.1 airmass distance). Therefore, some observers often use additional photometric measurements to correct the spectral fluxes. Since the extinction as a function of wavelength varies significantly within the N-band, also the spectral slope needs to be corrected, if the target and calibrator had been taken at different airmass.

Our goal is to explain the extinction in the mid-IR as a function of airmass. We further demonstrate that the extinction has a non-linear wavelength dependence within the N-band.
2 Data analysis

All observations of standard stars obtained with TIMMI2\(^1\) are archived from the beginning of operations in 2001 until present. The conversion factors between measured counts and known fluxes depend on the filter and lens scale used as well as the airmass (all systematically), but also vary with the sky conditions (statistically). A decreasing count rate as a function of rising airmass corresponds to an increasing conversion factor towards larger airmass.

We first separate all standard star measurements according to the filter and lens scale used. Data obtained before the TIMMI2 upgrade in October 2002 are treated separately because of different electronic gains in the previous readout system, but after a normalisation with the conversion factor for airmass AM = 1.0 both results are comparable.

In Fig. 1 we show the conversion factors (hereafter called Conv) for the N1 filter as a function of airmass. A more detailed version of this article with further illustrations will be available via the TIMMI2 webpage (cf. footnote). Note that a clear trend for Conv increasing with airmass can be seen, especially if you look towards the lower margin of the distribution.

Why can we constrain our analysis to the lower margin? For a given detector and instrument configuration there exists a well defined optimal sensitivity for a star, i.e. the least extincted count rate achieved for best weather conditions. This corresponds to a minimum conversion factor. On the other side, the sensitivity deteriorates arbitrarily with worse sky conditions, there is no clear maximum for the conversion factor. This is the reason why the distribution of points in Fig. 1 seems to be confined in lower y-direction but spreads towards higher y.

Since we need measurements obtained under identical weather conditions, it is sufficient to make a fit only with the lower-value points. We normalise for each filter the conversion factors by the value for AM = 1.0, in order to make comparable the measurements obtained before and after the TIMMI2 upgrade as well as to make these results comparable to other instruments.

3 Results

3.1 Differential extinction as function of airmass

We present relations, deduced as explained in Sect. 2, which describe the dependence of the atmospheric extinction with airmass (AM). Equation (1a), for example, signifies that at this wavelength the (spectral) flux must be corrected by 22\% to account for the extinction between AM = 1.0 and AM = 2.0. For mid-IR filters not given below the number of standard star measurements was not sufficient to calculate a firm result. Since the TIMMI2 archival of standard stars is an ongoing effort, we can add results for these passbands at a later stage.

\(^1\)http://www.ls.eso.org/lasilla/sciops/timmi
Fig. 1. Conversion factors as a function of airmass are displayed for the N1 passband. Squares are standard star measurements obtained since the TIMMI2 upgrade in October 2002, crosses symbolise data taken before this time. Especially watch the well defined rising of points between AM = 1.8 and AM = 2. The solid line represents the fit from which formula (1) is obtained.

In (1a–1d) AM represents the airmass of observation and Corr is the factor to correct the targets’ flux into measurements at airmass 1.0. Note that the TIMMI2 filters are not always named according to their central wavelength $\lambda_0$.

\[
\begin{align*}
  \text{N1 } (\lambda_0 = 8.6 \mu m) : & \quad \text{Corr}(AM) = 1 + 0.220 \times (AM - 1) \\
  \text{N8.9 } (\lambda_0 = 8.7 \mu m) : & \quad \text{Corr}(AM) = 1 + 0.208 \times (AM - 1) \\
  \text{N10.4 } (\lambda_0 = 10.3 \mu m) : & \quad \text{Corr}(AM) = 1 + 0.212 \times (AM - 1) \\
  \text{N11.9 } (\lambda_0 = 11.6 \mu m) : & \quad \text{Corr}(AM) = 1 + 0.116 \times (AM - 1)
\end{align*}
\]

For spectroscopy, both the target and calibrator must be flux corrected before their division. The wavelength dependence of Corr has to be taken into account. In a first approach, we use a linear interpolation between Corr for N1 and N11.9, since the best fits are achieved for those filters:

\[
\text{Corr}(\lambda, AM) = 1 + \left[\frac{0.220 - (0.220 - 0.116)/3 \times (\lambda - 8.6 \mu m)}{\lambda - 8.6 \mu m}\right] \times (AM - 1) 
\]

The factor '3' in (2) expresses the difference in wavelength between N1 and N11.9. Finally, Corr($\lambda, AM$) is multiplied with the uncorrected spectral flux $F(\lambda, AM)$:

\[
F_{\text{real}}(\lambda) = F(\lambda, AM) \times \text{Corr}(\lambda, AM) 
\]

In any data reduction script which also extracts the airmass from the file headers, (2) and (3) can be conveniently included. With this approximation al-
Table 1. Median N-band extinction coefficients for La Silla

| Filter | $K$ [mag/AM] |
|--------|--------------|
| N1     | 0.22         |
| N8.9   | 0.21         |
| N10.4  | 0.21         |
| N11.9  | 0.12         |

ready a significant improvement of the spectral fluxes is seen in Fig. 2, especially for large distances in airmass. At a later stage, when we can include further correction factors for other N-band filters, the flux correction can be improved to an even higher perfection.

3.2 N-band extinction coefficients

From the relative increase of atmospheric extinction between AM = 1.0 and AM = 2.0 we can, in principle, calculate the extinction coefficients $K$ for La Silla (usually given in mag/AM). These values depend on the observatory site, especially on the altitude and climatic conditions.

Table 1 summarises the median N-band extinction coefficients. Thereof an unextincted photometry with magnitudes $m_{\text{real}}$ can be obtained via the relation

$$m_{\text{obs}}(\text{AM}) = m_{\text{real}} + K \times \text{AM}. \quad (4)$$

The wavelength dependence of our extinction coefficients is similar to data for Mauna Kea, while the absolute values differ because of the other altitude.

4 Application to spectroscopic data

Formula (2) and (3) were tested with a cross-calibration of different standard stars taken from the same night. We used test data obtained both in December 2002 and September 2003. A calibrator at low airmass is taken while the objects were observed at higher airmass (see the headers of Fig. 2 for the actual airmass value).

Spectra shown in Fig. 2 were obtained in December 2002 when the detector had a dead column between approximately 9.0 $\mu$m and 9.8 $\mu$m. By intention we did not correct spectral line features in order to show how these may develop with increasing airmass between target and calibrator. Look especially to the CO$_2$ absorption features at 11.73 $\mu$m and 12.55 $\mu$m.

Further we derive spectrophotometric fluxes for the N11.9 filter and compare these with literature values. As shown in Table 2 and 3 our airmass correction improves the flux calibration both for targets observed at low and high airmass and reaches an accuracy up to 2% within the literature flux.
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Fig. 2. Illustrations of our airmass correction with a calibrator at airmass AM = 1.0 and targets up to AM = 2.0. The target spectrum is shown without airmass correction (dashed profile) and corrected (solid curve). A literature profile is overplotted (dotted). The quality of this correction may be further improved, when we can apply correction factors from the other N-band filters.

Table 2. Test of the airmass correction (AMC) with data taken on December 15th, 2002. The spectrophotometry in the N11.9 filter is shown with and without our airmass correction (AMC) for target and calibrator stars at varying airmass.

| Object     | AM (obj) | F (11.9 µm) [Jy] | Calibrator AM (cal) | no AMC [Jy] | with AMC [Jy] |
|------------|----------|------------------|---------------------|--------------|---------------|
| HD 32887   | 1.03     | 41.50            | HD 81797            | 1.51         | 45.58         | 43.14         |
|            |          |                  | HD 32887            | 1.86         | 47.82         | 43.59         |
|            |          |                  | HD 32887            | 2.02         | 48.46         | 43.43         |
| HD 32887   | 2.02     | 41.50            | HD 32887            | 1.03         | 35.67         | 39.79         |
|            |          |                  | HD 81797            | 1.44         | 37.63         | 40.09         |
|            |          |                  | HD 81797            | 1.51         | 39.09         | 41.27         |
|            |          |                  | HD 32887            | 1.86         | 41.02         | 41.71         |

Table 3. Test of the airmass correction (AMC) with data obtained on Sept. 13th, 2003.

| Object     | AM (obj) | F (11.9 µm) [Jy] | Calibrator AM (cal) | no AMC [Jy] | with AMC [Jy] |
|------------|----------|------------------|---------------------|--------------|---------------|
| HD 187642  | 1.27     | 24.28            | HD 4128             | 1.52         | 25.03         | 24.35         |
|            |          |                  | HD 169916           | 1.85         | 26.26         | 24.76         |
| HD 169916  | 1.85     | 22.35            | HD 187642           | 1.27         | 20.64         | 21.89         |
|            |          |                  | HD 196171           | 1.28         | 20.74         | 21.96         |
|            |          |                  | HD 4128             | 1.52         | 21.31         | 21.98         |