DOI: 10.18727/0722-6691/5382

Flux Calibration for VLT and ELT Spectrographs

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ESO offers a range of optical and infrared spectrographs on its telescopes, and more will be available once ESO's Extremely Large Telescope (ELT) starts operating. Some, but not all, science cases require the flux of spectra to be calibrated in relative or absolute units. The achievable accuracy of such a flux calibration differs with circumstances and instrument. In this article, we provide an overview of the methods and routinely obtained accuracy for current Very Large Telescope and future ELT spectrographs.

Introduction

Spectroscopic flux calibration means the conversion of a spectrum from the measured signal in e^{-} s^{-1} to physical flux units (erg cm^{-2} s^{-1} $Å^{-1}$ or W m^{-2} nm^{-1}). The wavelength dependent conversion is usually derived from the observations of spectrophotometric standard stars, whose absolute flux distributions are well known. A 'response curve' is determined by taking the ratio of the absolute flux distribution and the observed spectrum. Reduced science spectra are then multiplied by this response curve to flux-calibrate them.

There are two types of flux calibration, absolute and relative. Absolute flux calibration, by which the observed flux of a spectrum is converted to absolute flux units, is comparable to the photometric calibration of images. Absolutely flux-calibrated spectra represent the correct flux distribution of the object, both in value and shape, and can thus be compared directly to independently observed photometry or model spectra. Absolute flux calibration requires that the total flux that enters the telescope, for both the standard star and the science target, can be determined, and that the wavelength-dependent extinction for both a flux calibrator and the science observations can be determined. The former requirement is difficult to satisfy since flux lost by the finite slit width or fibre diameter needs to be measured or modelled. The latter requirement demands an accurate characterisation of the atmospheric conditions during a particular observing night.

For many science cases, such as radial-velocity or equivalent-width measurements, an absolute flux calibration is not necessary, and a relative flux calibration is sufficient to reach the science goals. Relative flux calibration corrects only the instrumental signatures in the spectra, such as for instance the spectral energy distribution (SED) of the flat field in the case of echelle data. Such a calibration results in spectra that are free from small-scale artefacts caused by the instrument such as wiggles and bumps, but the overall shape of the continuum may not accurately represent the physical flux distribution of the observed object. Reasons for discrepancies between the observed and the true shape include unaccounted slit losses, differences between the assumed and the actual extinction, and variations in extinction or instrument response between the observations of the standard star and the science target.

In this paper, we provide an overview of the methods and accuracy of spectral flux calibration of currently active Very Large Telescope (VLT) spectroscopic instruments.

VLT spectroscopic standard stars

Spectroscopic flux calibration relies on the availability of sufficiently bright spectroscopic standards with known absolute flux. These standards are then regularly observed to calibrate the combined throughput of the atmosphere, telescope and instrument optics. From these observations, a response curve can be derived. The response curve can then be used to convert, for a given airmass and instrument setup, the photon counts of a raw spectrum to physical units. The response needs to be tracked because of long-term changes in the instrument and telescope (for example, mirror reflectivity), as well as changing atmospheric conditions (for example, CO_2 or ozone abundance). Ideally the spectrum of a spectrophotometric standard star contains neither emission nor absorption lines, because such features can cause residuals in the ratio between reference spectrum and observed data, as a result of different resolution, imperfect wavelength calibration or radial velocity differences.

Traditionally, reference data with a variety of resolutions and accuracy, derived from ground-based or space-based observations for various spectral types, have been employed for flux calibration of VLT spectrographs. The most widely used catalogues for optical spectrographs are those from Hamuy et al. (1994) and the CALSPEC database of the Hubble Space Telescope (Bohlin, Gordon & Tremblay, 2014[1]; most of which are too bright and/or too northern for the VLT spectrographs). The data from Oke (1990) have systematic problems (as described in the original publication) and are therefore no longer used for any VLT instruments.

For observations in the infrared wavelength range spectrophotometric standards that are used for optical wavelength ranges are not necessarily suitable, because their spectra are usually known only up to about 1000 nm, and redder parts could contain spectral features or additional flux that affect the response determination. The VLT Imager and Spectrometer for mid-InfraRed (VISIR) uses as reference data spectral templates for late-type stars from Cohen et al. (1999) and the upgraded CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES+) uses model spectra of optical spectrophotometric standard stars of spectral types B4-A9.

For medium-resolution spectrographs covering wavelengths from the ultraviolet to the near-infrared like X-shooter, accurate photometric reference data are difficult to obtain. In such cases, stellar model spectra of hot white dwarfs can be used for flux calibration. The advantages of using model spectra (which are also available for some of the CALSPEC stars) are high spectral resolution and the absence of noise and atmospheric absorption features like telluric lines. Model spectra can be determined to a high level of accuracy for hot white dwarfs, which have relatively simple atmospheres, especially when compared to cool main sequence stars. From a practical point of view their spectra offer another advantage in that they have a small number of smooth and wide

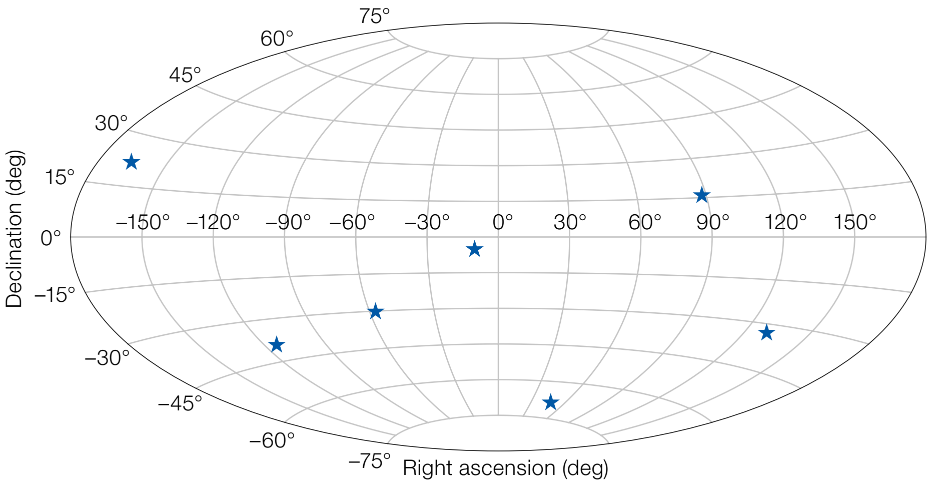

Figure 1. Distribution of the X-shooter spectrophotometric standard stars on the sky. The two northern stars are the HST CALSPEC standard stars GD71 and GD153.

absorption lines. This limits the impact of small deficiencies in the wavelength calibration or differences in resolution compared to the case of cool main sequence star spectra with many more and much narrower lines.

The finely sampled noise-free model spectra can be interpolated to the observed wavelength grid, so that the ratio of the reference and observed spectra can be determined at the full instrumental resolution instead of having to integrate the flux to the large bin size of low-resolution empirical reference data. This enables the fitting of small-scale instrumental variations that were previously lost. X-shooter was the first VLT instrument for which this approach was implemented consistently. The sample of X-shooter flux standard stars consist of six hot, white, hydrogen-atmosphere white dwarfs (two of which are also part of CALSPEC) and one hot, helium-rich pre-white dwarf. Figure 1 shows their distribution on the sky. Because the model spectra used as reference data do not contain telluric absorption, which becomes substantial in the near-infrared, a simple telluric correction was implemented. In addition, fit points were defined to avoid regions of very strong telluric absorption as well as the cores of the stellar lines, where differences in resolution and/or radial velocity can create strong but narrow residuals. The median values of the raw response over pre-defined windows at the fit points are then used to fit the response curve. More details can be found in Moehler et al. (2014). The overall slope of flux calibration using these model spectra is accurate to about 5% (Sana et al., 2024)

Calibration of VLT spectrographs

ESO operates a range of spectrographs that serve different science use cases and employ a range of different techniques to produce data of different natures. Accordingly, the flux calibration for each of them follows a specific plan. This calibration plan for each instrument is available at the instrument web pages[2].

Long-slit spectrographs

The three optical/NIR slit spectrographs currently operated at the VLT (the FOcal Reducer and low dispersion Spectrograph 2 [FORS2], the Ultraviolet and Visual Echelle Spectrograph [UVES], and X-shooter) perform only relative flux calibration, because the science targets are generally observed with narrow slits and the slit losses are hard to quantify automatically. Readers interested in this issue are referred to Chen et al. (2014) and Manara et al. (2021).

The experience with the X-shooter flux calibration resulted in the switch of the UVES reference data from the previous inhomogeneous collection to the X-shooter stars in 2020. Figure 2 compares the spectrum of the star κ Lep calibrated using the old and new reference data and pipelines[3]. One can clearly see that finely sampled reference data are required to catch the small-scale variations in the instrument response.

Observed spectra are affected by telluric absorption, whereas the physical stellar model spectra used as a comparison are not. In order to maximise the wavelength range usable to compute the response curve, the observed spectra are corrected for telluric absorption which depends on the atmospheric condition at the time of observation. In the X-shooter pipeline this correction is performed by selecting the best-fitting telluric model spectra from a library of model spectra (Kausch et al., 2015). For UVES spectra, wavelength regions with strong telluric absorption are excluded from the fit in the standard settings of 760 nm and 860 nm.

FORS2, with its lower resolution, has so far relied primarily on the standard stars of Hamuy et al. (1994). The spectra were masked to avoid telluric and stellar lines, which in some cases resulted in a large fraction of the spectrum being masked. The FORS pipeline is currently being updated to use the same standard stars and methods as UVES and X-shooter. In the case of FORS, the standard-star model spectra are convolved to lower spectral resolution to avoid large residuals. The telluric correction is carried out by directly fitting a physical model to the observed spectra (Smette et al., 2015; Kausch et al., 2015). The latest release of the FORS pipeline contains these improvements.

Fibre spectrographs (ESPRESSO)

The Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) is a high-resolution spectrograph that uses fibres instead of physical slits. Several fibres are used to form a 'pseudo slit'. The total flux collected by a fibre depends on the exact two-dimensional positioning of the fibres relative to the source. It is therefore even more challenging to quantify the 'slit' losses for a particular observation.

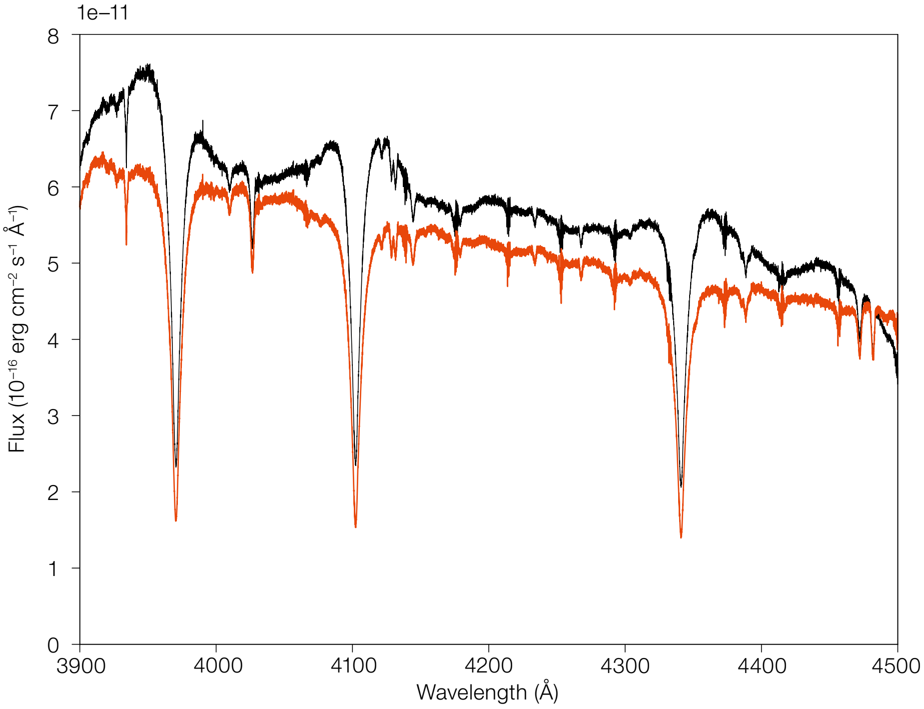

Figure 2. Comparison of the flux-calibrated spectrum for the bright star κ Lep (observed 2019-01-17T01:01:23.629), processed with the response curve derived from the associated flux standard star EG21. The black spectrum shows the result of the flux calibration using the old UVES response determination, the red one the result using the new UVES response determination (offset for easier comparison).

ESPRESSO uses very low-resolution spectra of bright stars derived from ground-based observations (Hamuy et al., 1994), i.e., including telluric absorption, as reference data. The pipeline corrects the observed flux for slit losses taking into account the seeing (described by a Moffat function) compared to the diameter of the fibre. Slit losses become significant if the seeing disc is larger than the fibre. The effects of positioning uncertainty are not considered. The pipeline computes the absolute efficiency at reference wavelengths by comparing it to the reference spectrum. The result is then interpolated to the ESPRESSO wavelength scale using cubic splines. The precision of the flux calibration is expected to be low because of the highly variable fibre losses.

Integral field spectrographs (MUSE, KMOS, ERIS-SPIFFIER)

Integral field spectrographs (IFUs) produce full position–wavelength cubes of a field using an image slicer that cuts the field of view into slices that are then fed to spectrographs. They do not suffer from slit losses during the observation since the flux is collected mostly independent of the positioning of the sources relative to the detector. Slit losses can occur during the extraction of spectra for individual targets, but these can in principle be quantified to very high accuracy. The goal of the flux calibration of IFUs is to convert the total flux contained within each wavelength plane of the data cube to physical units.

The Multi Unit Spectroscopic Explorer (MUSE) provides absolute flux calibration and uses a mixed set of reference spectra, some of them high-resolution model spectra and some data observed from space with lower resolution, all without telluric absorption. The MUSE resolution is sufficiently low to cause problems if high-resolution model spectra are used as reference data without convolving them first to a lower resolution, as for FORS2. The pipeline determines a first response curve by comparing the observed spectrum to the reference one. Next it interpolates across regions of telluric absorption and determines a telluric correction spectrum from the normalised spectrum, assuming that the standard star spectrum is smooth across the telluric regions. The final response curve is then linearly extrapolated to the largest possible wavelength range and smoothed.

The *K*-band Multi Object Spectrograph (KMOS) also provides absolute flux calibration but uses as reference data hard-coded model spectra per spectral type and magnitude, which consist of a Planck blackbody curve with added absorption lines, whose depth is adjusted to the observed data. The final response curve is thus a combination of instrumental response and telluric absorption

The Enhanced Resolution Imager and Spectrograph (ERIS-SPIFFIER) uses the same standard stars as X-shooter and a similar procedure to determine the response curves.

Spectrographs without flux calibration

The VLT spectrographs VISIR (slit) and CRIRES+ (fibre) monitor the instrument throughput/efficiency using standard stars, but do not flux-calibrate the science data. For details see Table 1.

For a multi-fibre instrument like GIRAFFE the cost of observing time to obtain flux calibration was considered too high. The throughput of the instrument is monitored only in the IFU (ARGUS) mode.

The ERIS Near Infrared Camera System (ERIS-NIX) instead does not monitor the efficiency of its long-slit mode because there are no suitable flux standard stars for the *L* and *M* bands.

The Spectro-Polarimetric High-contrast Exoplanet REsearch instrument Integral Field Spectrograph (SPHERE-IFS) observes some of the CRIRES flux standard stars, but the data are not processed.

ELT spectrographs

All Extremely Large Telescope (ELT) instruments will use adaptive optics, which can cause variable flux losses

Instrument	Mode	Wavelength coverage (microns)	Resolution	Flux calibration	Telluric correction of flux std	Source for reference data	Type of reference data	Accuracy of flux calibration
CRIRES+	Slit	0.95–5.3	43000 / 86000	No, science goals do not require it – this instrument is designed to measure radial velocities and weak lines; efficiency monitoring only	No	Model spectra from T. Rauch & P. Coelho (priv. comm.)	Model	N/A
ERIS NIX	Slit	3.05–4.05	900	No, no *L* or *M* band spectro-photometric standards are available	N/A	N/A	N/A	N/A
ERIS SPIFFIER	IFU	1.09–2.47	5000 / 10000	Yes	Yes	Moehler et al. (2014)	Model	Unknown
ESPRESSO	Fiber	0.38–0.79	70000–190000	Yes	No	Hamuy et al. (1994) (HR stars)	Ground	Unknown
FORS2	Slit	0.33–1.1	260–5200	Yes	No	ground Hamuy et al. (1994); space/model HST CALSPEC	Ground / model / space	Unknown
GIRAFFE	Fiber	0.37–0.95	11000–39000	No, because science cases do not need it; observations of flux standards are not part of the calibration plan	N/A	N/A	N/A	N/A
GIRAFFE	IFU	0.37–0.95	11000–39000	No, because science cases do not need it; efficiency monitoring only	No	N/A	N/A	N/A
KMOS	IFU	0.8–2.5	2000–4200	Yes	No	Extended Hipparcos Compilation (XHIP) (Anderson & Francis, 2012)	Model (blackbody + absorption lines, based on spectral type)	10% on continum ~15% wiggles in case of good seeing observations
MUSE	IFU	0.47–0.93	3000	Yes	Yes	Moehler et al. (2014); CALSPEC (HST)	Model / space	Continuum 5–10%, with long-scale wiggles < 5%
SPHERE	IFU	0.95–1.65	30 / 50	No, because science casse do need it;observations of flux standards are not part of the calibration plan	N/A	N/A	N/A	N/A
UVES	Slit	0.3–1.1	40000–110000	Yes	No	Moehler et al. (2014)	Model	Unknown
VISIR	Slit	7.7–24.0	350 / 25000	No, because flux uncertainty is dominated by the extremely high background, the sources are a percent or less than the sky contribution and the Poisson errors form the background is huge;efficiency monitoring only	No	Cohen et al. (1999)	Space	N/A
X-shooter	Slit	0.3–2.5	3200–18400	Yes	Yes	Moehler et al. (2014)	Model	Small-scale wriggles about 2%; slope about 5–10% (Sana et al., 2024)

Table 1. An overview of the type of flux calibration implemented at the VLT spectrographs.

and therefore present special calibration challenges that are not addressed here.

The High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI) provides low- to medium-resolution IFU spectroscopy at 0.45–2.8 microns over a range of resolving powers and will use the X-shooter flux standard stars.

The Mid-infrared ELT Imager and Spectrograph (METIS) provides high-resolution IFU spectroscopy at 3–5 microns and low-resolution slit spectroscopy at 3–13 microns. It will use the same flux standard stars as VISIR.

The Multi-AO Imaging Camera for Deep Observations (MICADO) offers medium-resolution IFU and slit spectroscopy at 0.8–2.5 microns. Suitable flux standard stars have been defined from X-shooter observations of nearby hot white dwarfs.

Summary

Spectrophotometry can be carried out with the majority of VLT spectrographs, although with varying accuracy. A summary of the current state is given in Table 1. The calibration plan for flux calibration is the result of a careful instrument-specific cost-benefit analysis for each instrument, that might evolve over the course of time. In some cases, it might be necessary for science programmes to collect additional calibration data to improve on the flux calibration that can be achieved with the standard calibration plan. Any additional time needed for such extra nighttime calibrations must already be requested in Phase 1.

Acknowledgements

We thank Lodovico Coccato, Mark Neeser, Isabelle Percheron, and Valentin Ivanov for providing substantial parts of the information presented here.

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Links

[1] CALSPEC database: https://www.stsci.edu/hst/instrumentation/reference-data-for-calibration-and-tools/astronomical-catalogs/calspec

[2] Paranal instrument details: http://www.eso.org/sci/facilities/paranal/instruments.html

[3] ESO data reduction pipelines: https://www.eso.org/sci/software/pipe_aem_main.html

Y. Beletsky (LCO)/ESO

Looking almost like a watercolour painting, this stunning photograph of comet C/2024 G3 (ATLAS) was taken by Yuri Beletsky on 19 January from ESO's Paranal Observatory in Chile. The comet poses next to one of the Auxiliary Telescopes of ESO's Very Large Telescope Interferometer.