BAAA, Vol. 64, 2023
R.D. Rohrmann, C.H. Mandrini, C.E. Boeris & M.A. Sgró, eds.

Asociación Argentina de Astronomía
Boletín de artículos científicos

NISCAL: Near Infrared Spectroscopy Calibrator

C.G. Díaz[1], G. Gaspar[2] & R.J. Díaz[3]

[1] *Instituto de Ciencias Astronómicas, de la Tierra y del Espacio, CONICET–UNSJ, Argentina*
[2] *Observatorio Astronómico de Córdoba, UNC, Argentina*
[3] *Gemini Observatory, EE.UU.*

Contact / gonzalodiaz@conicet.gov.ar

Resumen / Las observaciones espectroscópicas infrarrojas suelen ser acompañadas por una estrella de comparación (o "telúrica") para corregir la absorción atmosférica que varía rápidamente y depende de las condiciones de observación (ej. vapor de agua, temperatura, masa de aire). Aquí presentamos NISCAL, un código que utiliza el espectro de la estrella observada y una lista de espectros estelares (sintéticos u observados), para optimizar la corrección telúrica y la calibración en flujo, automatizando la búsqueda del mejor ajuste, minimizando la contribución del espectro estelar a la función de transmisión, y siguiendo los errores para estimar el nivel de incertidumbre en el espectro final. NISCAL calcula la diferencia en velocidad radial, busca el espectro que mejor se ajusta a la estrella observada, obtiene la función de transmisión al remover el espectro estelar, y aplica la corrección telúrica a los datos de ciencia. Además, ofrece una calibración en flujo con la magnitud de la fuente científica o de la estrella telúrica, o con datos de una estrella estándar de flujo, donde se consideran todas las pérdidas por apertura de ranura según el perfil de luz definido por el usuario. Su versión actual es para espectroscopía de ranura de objetos puntuales y está siendo desarrollado para otros modos de espectroscopía. Presentamos el efecto de la corrección telúrica y la calibración en flujo en la relación señal-ruido del espectro final con observaciones de Flamingos-2 en Gemini Sur.

Abstract / Infrared spectroscopic observations are often accompanied by a comparison star (or "telluric") to correct for rapidly varying atmospheric absorption that depend on observing conditions (eg water vapor, temperature, air mass). Here we present NISCAL, a code that uses the spectrum of the observed star and a list of stellar spectra (synthetic or observed), to optimize the telluric correction and flux calibration, automating the search for the best fit, minimizing the contribution of the stellar spectrum to the transmission function, and following the errors to estimate the level of uncertainty in the final spectrum. NISCAL calculates the difference in radial velocity, searches for the spectrum that best fits the observed star, obtains the transmission function by removing the stellar spectrum, and applies the telluric correction to the science data. In addition, it offers a flux calibration with the magnitude of either the scientific source or the telluric star, or with data from a flux standard star, where all slit losses are considered based on the user-defined light profile. Its current version is for slit spectroscopy of point sources and is being developed for other spectroscopy modes. We present the effect of telluric correction and flux calibration on the signal-to-noise ratio of the final spectrum with observations of Flamingos-2 in Gemini South.

Keywords / atmospheric effects — methods: observational — techniques: spectroscopic

1. Introduction

The short time scale of the atmospheric absorption is one of the main sources of error in flux calibration of infrared spectroscopic observations. The absorption spectrum (Fig. 1) strongly depends on the atmospheric conditions during the observation, including air mass, water vapor, temperature and composition. Thus, scientific observations are typically followed by the observation of a comparison star (or "telluric star") to record the atmospheric transmission in its spectrum, which is later retrieved during data reduction and applied as a correction factor (termed "telluric correction") to the science data. The telluric star approach imposes limitations to be taken into account when planning (or reducing) spectroscopic observations:

1) the quality of the telluric correction decreases with the duration of science observation (the agreed limit is 1.5 hours),
2) the error associated with the telluric correction for weak sources is greater because it requires longer exposures, and
3) combining data from several nights implies combining data with different telluric corrections.

Given the importance of removing atmospheric absorption, we are developing a tool to optimize the process.

NISCAL is a tool written in Python that calculates the telluric correction function with the spectrum of an observed star and a library of comparison stellar spectra or templates (synthetic or observed), from which it chooses the best option and provides a follow-up of the signal-to-noise ratio. The current version has been tested with synthetic spectra from the Göttingen Stellar Library* (GSL, Husser et al., 2013) and observed spectra from the X-shooter Spectral Library** (XSL DR3,

*https://phoenix.astro.physik.uni-goettingen.de
**http://xsl.astro.unistra.fr/page_dr3.html

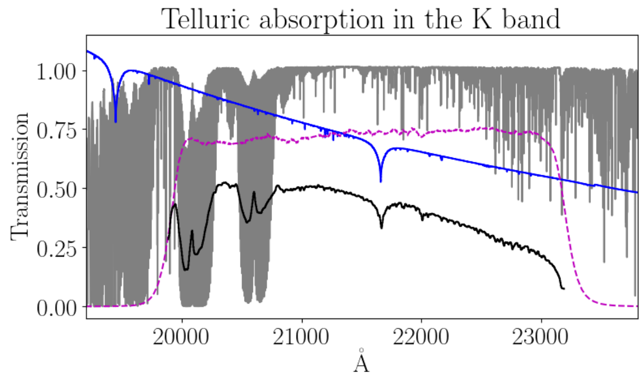

Figure 1: Characteristics in the region of K band. Grey: example of atmospheric transmission at Cerro Pachón. Magenta: Flamingos-2 Ks filter transmission. Blue: Scaled synthetic stellar spectrum ($T = 9000$ K) from the GSL (Husser et al., 2013). Black: Star HD21875 observed in Ks with Flamingos-2 for program GS-2018B-Q-303 (PI: G. Díaz).

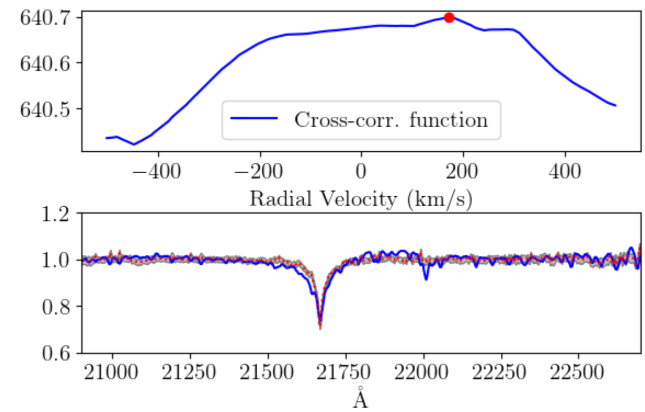

Figure 2: *Top:* Correlation function between the template xsl_HD74721_A0V and the telluric star HD21875, the maximum corresponds to 172 $\mathrm{km\,s^{-1}}$, indicated with the red dot. *Bottom:* Telluric star (blue) and template displaced by 172 $\mathrm{km\,s^{-1}}$ (red line with gray-shaded errors).

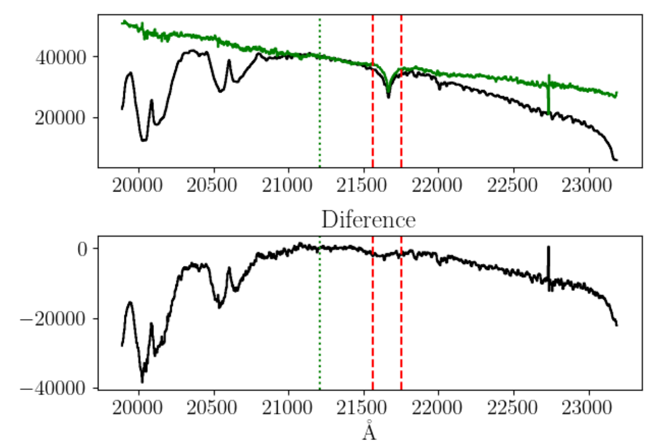

Figure 3: *Top:* Template xsl_HD174240_A1IV (green) and telluric star HD21875 (black) scaled at 2.12 μm (green dotted vertical line). *Bottom:* Template-telluric difference for quality control. Red dashed vertical lines indicate the range where the accuracy of the template is evaluated.

Verro et al., 2022).

The objective of NISCAL is to optimize telluric correction and flux calibration in multi-epoch spectroscopic data in all modes: in long slit (LS), multi-object (MOS), and integral field (IFU). The final version will provide three flux calibration modes: the magnitude of the source, the magnitude of the telluric star, and observations of a flux standard star.

2. Summary of the process

NISCAL depends on ASTROPY (Astropy Collaboration et al., 2013, 2022), SCIPY (Virtanen et al., 2020), PYASTRONOMY (Czesla et al., 2019), SPECUTILS (Earl et al., 2022), and MATPLOTLIB (Hunter, 2007).

The code follows a sequence of steps which are described in the following subsections.

2.1. Telluric correction.

- The input spectra (science and telluric star) are loaded for processing. These must be 1D reduced spectra including all steps necessary up to the extraction of a 1D spectrum, i.e. bias and overscan subtraction, dark current correction (if needed), flat field correction, wavelength calibration and sky subtraction (e.g. the output of the IRAF data reduction pipeline).
- The radial velocity of the telluric star with respect to each template spectrum is calculated (Fig. 2, top panel), unless it is defined in the input. Then, each template is shifted in velocity to match the telluric star (Fig. 2, bottom panel).
- The templates are scaled to match the telluric star spectrum at a defined wavelength (Fig. 3, top panel).
- The telluric corrections (one for each template) are calculated as the quotient: telluric / template.
- The residuals of the telluric-template difference (Fig. 3, bottom panel) are analyzed to choose the best template based on the standard deviation, asymmetry and kurtosis of the residuals within a defined region of the spectrum for quality inspection.
- The scientific spectrum is divided by the automatically selected (or user selected) telluric correction, and the result is recorded in a new ".fits" file.

2.2. Slit aperture correction

- The slit aperture correction (or "slit loss") is calculated for the science and the telluric star, as the fraction of the light profile within a slit of a given width, indicated by the user. The current version uses a Gaussian Point Spread Function model with $\sigma = FWHM/2.3548$, where $FWHM$ is the full width at half maximum of the light profile in pixels (Fig. 4) and must be provided for both science and telluric star.
- The aperture correction for the science and the telluric star are applied as scaling factors to each spectra in counts per second ($\mathrm{ADU\,s^{-1}}$). This step is relevant if

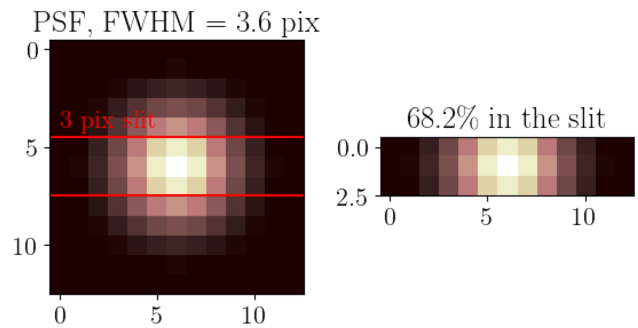

Figure 4: Slit aperture correction (or slit-loss) for a point source with a PSF of $FWHM = 3.6$ pixels and a slit width of 3 pixels. The PSF was simulated with a Gaussian kernel.

the magnitude of the science object is unknown. It must be included for flux calibration based on flux standard stars or telluric stars.

2.3. Flux calibration based on 2MASS photometry of the source

- Flux calibration based on photometry is achieved by scaling the spectrum so the total flux in the corresponding filter is equal to the total flux from the photometry (Fig. 5). The errors in the photometry are included by calculating two flux scaling factors corresponding to (MAG + ERROR) and (MAG - ERROR). The result is recorded in a new ".fits" file. The aperture correction is unnecessary in this calculation.

2.4. Flux calibration based on 2MASS photometry of the telluric star

The uncertainty of an flux calibration based on the telluric star will be dominated by the flux variability of that star. This flux calibration is applied during the telluric correction, thus the input science spectrum must be uncorrected for telluric absorption. However, the slit aperture correction must be applied to the science and telluric star spectra.
- The previously selected template (see Sect. 2.1) is calibrated in flux matching it to the 2MASS photometry of the telluric star.
- The telluric star spectrum corrected by aperture (see Sect. 2.2) is divided by the flux calibrated template to obtain a telluric flux calibrated spectrum, which is also a flux calibration function.
- The slit-loss corrected science spectrum in ADU s^{-1}, without telluric correction, is divided by the flux calibrated telluric correction and recorded in a new ".fits" file.

3. Summary and future work

NISCAL optimizes telluric correction and flux calibration, minimizing the contribution of the stellar spectrum to the telluric correction, automating the search for the best available stellar template, and tracking errors to

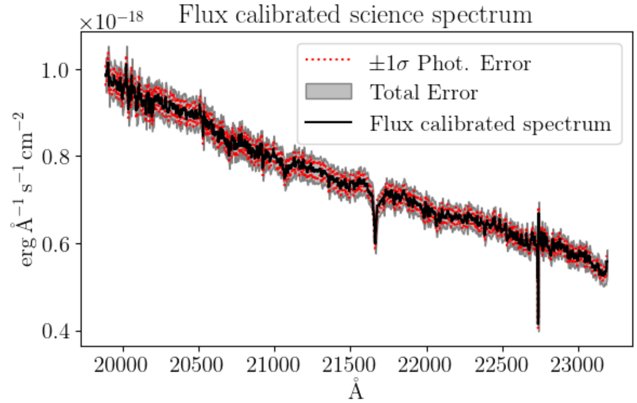

Figure 5: Output of NISCAL. Flux calibrated spectrum of standard star FS112 based on 2MASS photometry. The grey area indicates the total error including the spectroscopic error array from the IRAF data reduction and the photometric error (red dotted lines).

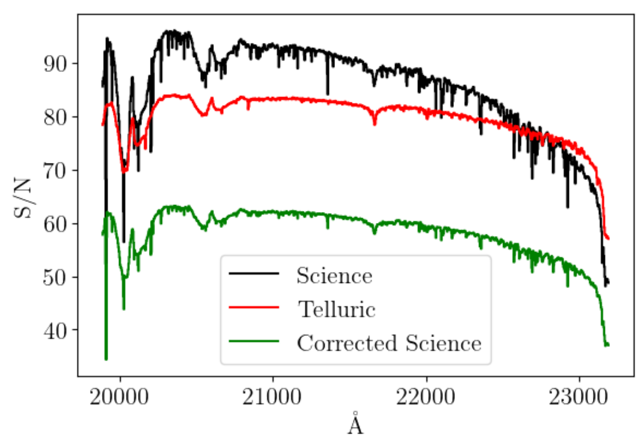

Figure 6: Signal-to-noise ratio of the observed science spectrum (black), the observed telluric star (red), and the final science spectrum after telluric correction (green).

estimate the level of uncertainty in the final spectrum (Fig. 6). The current version is for slit spectroscopy of point sources and is being developed for: LS spectroscopy of extended objects, IFU spectroscopy, MOS, standard star flux calibration, and multi-epoch data.

Acknowledgements: C.G. Díaz acknowledges the support of the Observatorio Astronómico de Córdoba.

References

Astropy Collaboration, et al., 2013, A&A, 558, A33
Astropy Collaboration, et al., 2022, apj, 935, 167
Czesla S., et al., 2019, PyA: Python astronomy-related packages
Earl N., et al., 2022, astropy/specutils: v1.9.1
Hunter J.D., 2007, Computing in Science & Engineering, 9, 90
Husser T.O., et al., 2013, A&A, 553, A6
Verro K., et al., 2022, A&A, 660, A34
Virtanen P., et al., 2020, Nature, 17, 261