DOI: 10.18727/0722-6691/5148

On the Telluric Correction of KMOS Spectra

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The presence of strong absorption lines in the atmospheric transmission spectrum affects spectroscopic observations, in particular those in the near- and mid-infrared. Therefore, there is the need to correct scientific observations for this effect, a process known as telluric correction. The use of a detailed model of the atmospheric transmission spectrum brings several advantages over the method of empirically deriving corrections using observations of a telluric standard star. In this paper, we discuss and compare the two methods applied to *K*-band Multi-Object Spectrograph (KMOS) observations and show the improvements in the quality of the final products obtained by implementing the modelling technique offered by the ESO molecfit sky tool.

Correction for atmospheric transmission in spectroscopic data

Ground-based spectroscopic observations are strongly affected by the Earth's atmosphere. In particular, spectra of objects taken in the near- and mid-infrared wavelength ranges are characterised by a forest of absorption lines, called telluric absorptions. These features are caused by (mainly water and OH) molecules present in the atmosphere that absorb the light from astrophysical sources. The standard way to correct for this effect is to acquire a spectrum of a bright and featureless star close in time and airmass to the scientific target, and compare it either with its model or, if available, with a spectrum taken from space. This empirical strategy, however, has some drawbacks. First, it requires additional (expensive) telescope time. Second it can be complicated to separate atmospheric and instrumental effects, (for example, the instrument response) if a large wavelength range of stellar continuum is absorbed by blended absorption lines. Last but not least, the noise and imperfections in the data reduction of these stars are inevitably propagated to scientific spectra.

Alternatively, one can model the atmosphere, generate its transmission spectrum and apply it to observations. The model itself can be obtained by fitting well-defined telluric lines to the spectrum of either a standard star or a sufficiently bright science target. In general, a model depends on four components: (a) a radiative transfer model; (b) a set of parameters that determines the absorption and transmission properties of individual molecules; (c) atmospheric profiles of temperature, humidity, and volume mixing ratio for the molecules involved; and (d) instrumental parameters such as spectral resolution. This model-dependent approach has several advantages over the empirical method. First, no additional noise or sources of error coming from the standard star observations and reduction are propagated to the science spectra. Second, it allows additional components to be taken into account, such as the amount of precipitable water vapour from external sources and inaccurate wavelength calibrations, and differences between the observations of the standard star and the science target (for example, airmass and spectral resolution). On the other hand, using a model of the atmosphere for the telluric correction risks the introduction of systematics because of limitations in the modelling. In practice, the artefacts caused by such systematics are outweighed by the improvements made in the corrections.

The model approach has been developed in a software package named molecfit (Kausch et al., 2013; Smette et al., 2015). Molecfit uses (a) the Line-by-line Radiative Transfer Model [1] (LBLRTM) algorithm (Clough, Iacono & Moncet, 2005) to compute the radiative transfer model, (b) the high-resolution transmission molecular absorption (HITRAN) database [2] for the molecular parameters, (c) Global Data Assimilation System [3] (GDAS) and ESA Michelson Interferometer for Passive Atmospheric Sounding [4] (MIPAS) atmospheric profiles for temperature, humidity, water vapour and other molecules, and (d) analytic functions or user-provided files for the instrumental spectral resolution. The fit to the telluric absorption lines in the observed spectra provides the integrated column density of individual molecules. Future versions will further improve the quality of the model by including real-time measurement of precipitable water vapour and other molecules along the line of sight of the exposures.

In the following, we describe the improvements in the quality of KMOS (Sharples et al., 2013) spectra obtained with the model approach using molecfit with respect to the empirical method. Data were reduced using the KMOS pipeline (Davies et al., 2013). In the model approach, the atmospheric model was obtained by fitting a number of predefined telluric lines on a standard star spectrum observed close in time to the scientific data (i.e., the same standard star that was used in the empirical method). The telluric correction over the full wavelength range was then computed accounting for the differences in airmass and spectral resolution between the scientific spectrum to correct and the standard star. As a test-bench for comparison, we processed one month of KMOS data and compared the results obtained with these two different telluric correction strategies.

Benefits of the molecfit strategy for KMOS observations

As described previously, because the molecfit correction is based on a model, it does not add noise to the final products or defects such as uncorrected cosmic rays that are embedded in the standard star spectrum. Figure 1 shows a comparison between the mean signal-to-noise per pixel of the datacubes obtained by correcting the telluric absorption directly with a standard star (i.e., the empirical method) and by modelling the atmospheric absorptions with molecfit. The signal-to-noise is measured in a wavelength region that is free of sky or telluric lines, and therefore is an indication of the noise added by the telluric correction. As expected, the data corrected with

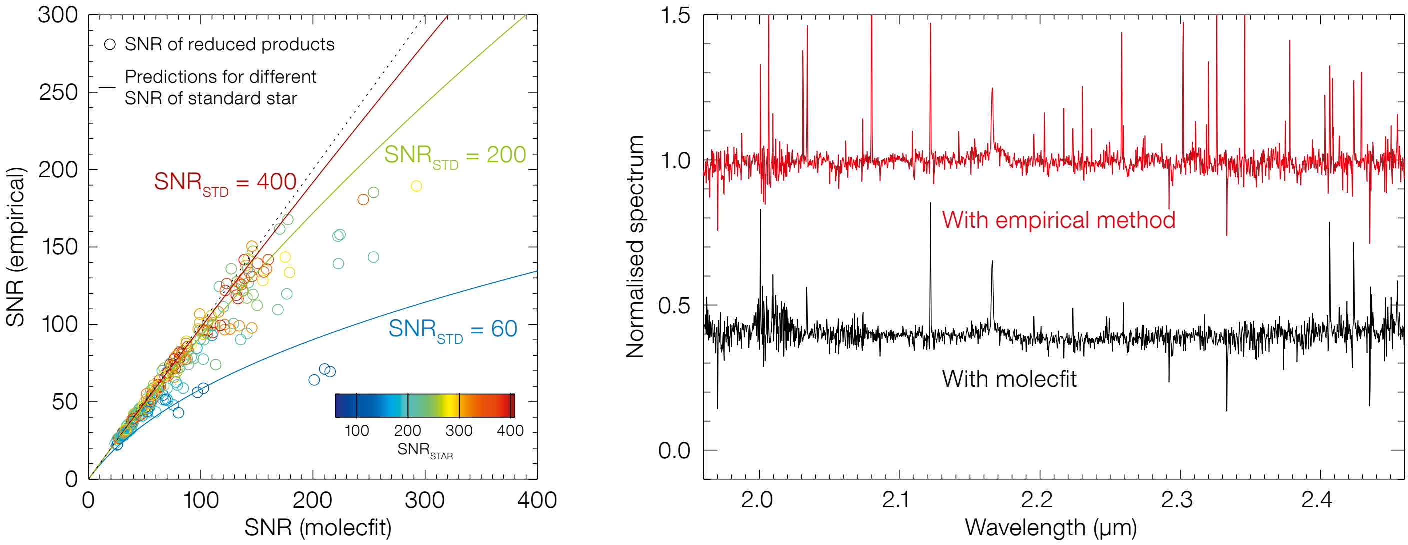


Figure 1. Left panel: Comparison between the signal-to-noise ratio (per pixel) of the final KMOS datacubes obtained with the empirical corrections and the method with molecfit on-standard model for the telluric correction. The colour of the symbols is proportional to the signal-to-noise of the telluric star used in the data reduction; predicted trends for several values of the signal-to-noise of the telluric standard are shown. The dashed black line shows the 1:1 relation. Right panel: Example of spectra corrected with the empirical corrections (in red) and with the model approach with molecfit (in black) for the dataset KMOS.2018-10-23T07:35:07.185.

molecfit contain less noise; the effect is much more visible for bright objects which have signal-to-noise ratios close to those of the telluric standard stars. No major improvement is expected for objects with signal-to-noise < 50, because the noise in the telluric standard is negligible with respect to the total noise in the data. Even with the model approach there are systematic artefacts in the reduced spectrum that are due to residuals in the sky subtraction or cosmic ray cleaning. However, with the empirical approach the number of artefacts is higher; these additional artefacts are not due to the sky subtraction in the science spectra (in fact, the same procedure as in the model approach is used). Some of these are inherited from imperfections in the reduction of the standard star while others are due to the limitations of the empirical method in dealing with differences between the observations of the science and the telluric star (see Figures 2 and 3).

One of the limitations of the empirical telluric correction method is that the telluric star and the science target are observed at different airmasses. The KMOS night calibration plan is designed to minimise such differences; for example, a telluric standard is observed every two hours at airmasses close to the scientific targets observed during the night. However, differences up to ~ 0.4 in airmass are unavoidable owing to observational constraints, in particular during observations in visitor mode during which the requirements for the observation of the telluric standard stars are relaxed. The consequence is that some telluric lines are over- or under-corrected by up to or over 10%, because the column density of the molecules, and therefore the atmospheric transmission, is linked to the airmass. The empirical approach offered by the KMOS pipeline does not account for such airmass differences, whereas the model approach does. Figure 2 shows the change in intensity in the telluric line at 1.27 µm for a difference in airmass of Δz = 0.34, and its effects on the corrected science spectrum; accounting for this difference overestimates the absorption feature at 1.27 µm by ~ 10%. The bottom panel of Figure 2 shows a systematic artefact at 1.27 µm, which is due to there being no correction for the difference in airmass between science and standard star observations.

Another limitation of the empirical method is that taking a telluric calibration in each of the 24 arms is time consuming. Therefore, the large majority of programmes observe a telluric standard star in only 3 out of the 24 arms available in KMOS, i.e., one per detector. However, the spectral resolutions of the various arms are different, therefore the absorption features in atmospheric transmission will have different shapes in different arms. This means that the observed shape of the absorption lines in telluric correction determined for a star observed with one arm does not fully match the shape of the telluric lines of a scientific spectrum obtained with another arm. This issue can be taken into account in the model approach, by including a set of static calibrations that reproduce the wavelength dependency of the instrumental spectral resolution for each arm and instrument configuration. These calibrations are included in the KMOS pipeline distribution and allow one to compute the telluric correction for each arm with the exact shape of the absorption lines, regardless of which arm the telluric standard was observed with. Figure 3 compares the effects of taking and not taking into account the spectral resolution during the modelling in the final KMOS products. The shape of the absorption features can differ by 10% or more, leading to artificial features in the final corrected spectrum.

Molecfit implementation in the KMOS instrument pipeline

The original molecfit software interface does not support the use of KMOS data

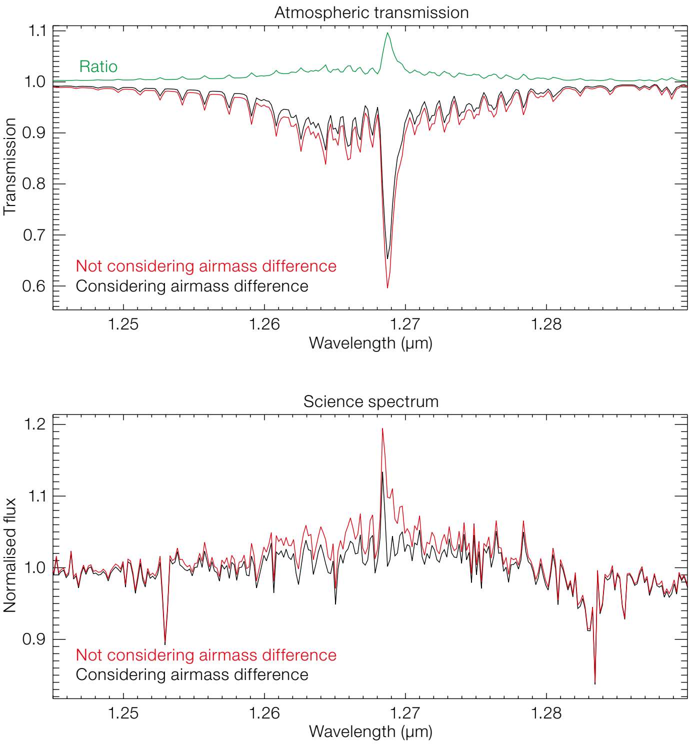


Figure 2. Comparison between the outcome of different molecfit models that account for (black) and ignore (red) the airmass difference between the standard star and the science spectra. The top panel shows the atmospheric transmissions and their ratio (in green). The airmass difference between the two models is $\Delta z = 0.34$. The bottom panel compares the science spectra corrected with these different transmissions. The dataset used here is KMOS.2016-12-21T03:18:57.095.

directly, because of the complicated multi-extension structure that requires special treatment. In order to provide a convenient interface, the molecfit algorithms have been integrated into the KMOS pipeline, which now offers three strategies to correct for telluric absorptions in the observations:

1. Use the telluric standard star spectrum directly to correct the science data, i.e., the empirical method.
2. Use the standard star spectrum as reference to model the atmosphere and derive its transmission to correct science data on the same night (we call this the molecfit on-standard approach).
3. Use one science spectrum as a reference to model the atmosphere and derive its transmission to correct the science spectrum itself or other science data in the same observing block (we define this as the molecfit on-science approach).

The empirical method is much faster, but generally does not return the best results. Nevertheless, it is useful for a quick look at the data or in those cases where the atmospheric fit does not converge. The molecfit methods are computationally slower but return the best results in the vast majority of cases. Both the molecfit on-standard and on-science approaches model the atmosphere by fitting a number of telluric absorption features in a reference spectrum. In the on-standard approach, the default wavelength regions of the recipe can safely be used, whereas for the on-science approach it is advisable to carefully adjust the fitting regions avoiding intrinsic features of the science spectrum. Then, the full telluric correction is obtained for the entire wavelength range and it accounts for the difference in airmass between the reference and science spectra. A set of static calibration files provide the recipes with tables giving the wavelength-dependent instrument spectral resolution and instrument response for each integral field unit (IFU), grating, and instrument rotator angle. Figure 4 illustrates the data reduction cascades due to the two different molecfit approaches. For each spectrum, the user can select a reference scientific exposure from which to obtain the atmospheric transmission. It can be the same target or another; for example, a bright target can be used to compute the correction for all other observations in the same observing block. The loop is rerun for each input exposure accounting for changes in airmass and spectral resolution.

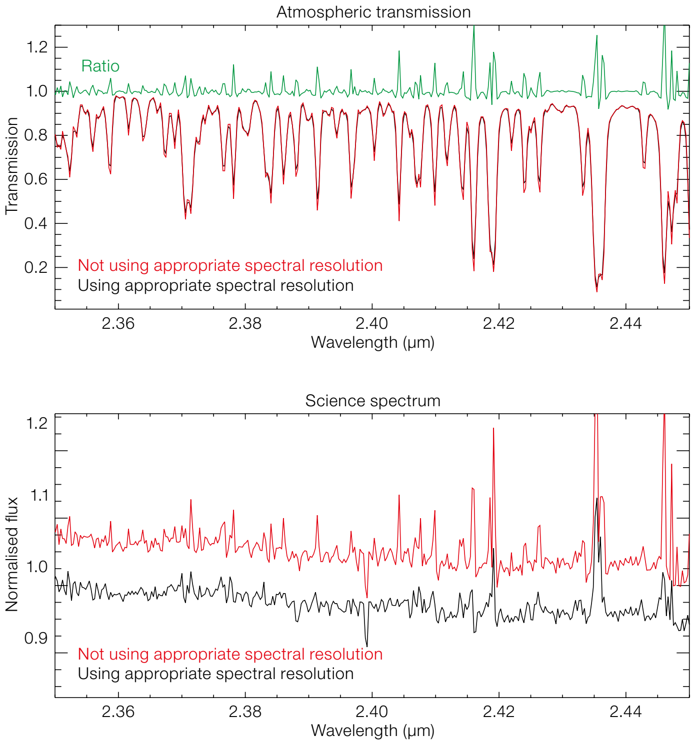


Figure 3. Comparison between the outcome of different molecfit models that account for (black) and ignore (red) the differences in spectral resolution between the arm used to observe the standard star and the arm used to observe the scientific target. The top panel shows the atmospheric transmissions and their ratios (in green). The bottom panel compares the telluric-corrected science spectra (arbitrarily shifted). The file used here is KMOS.2017-02-13T05:45:03.492.

All three correction strategies have been integrated into the data reduction workflow that can be executed within the EsoReflex data reduction environment (Freudling et al., 2013). The KMOS workflow includes automatic organisation of the data and interactive tools to visualise and control the telluric correction as well as other reduction steps (Figure 5). In particular, it includes a tool to select

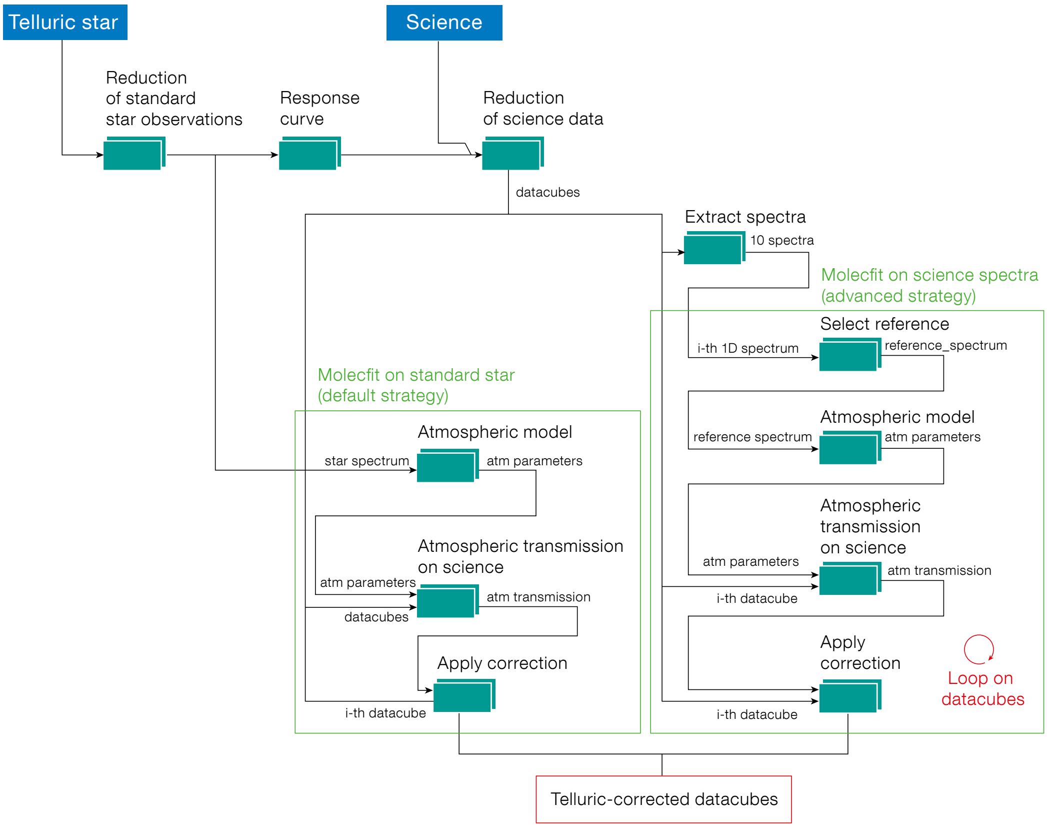
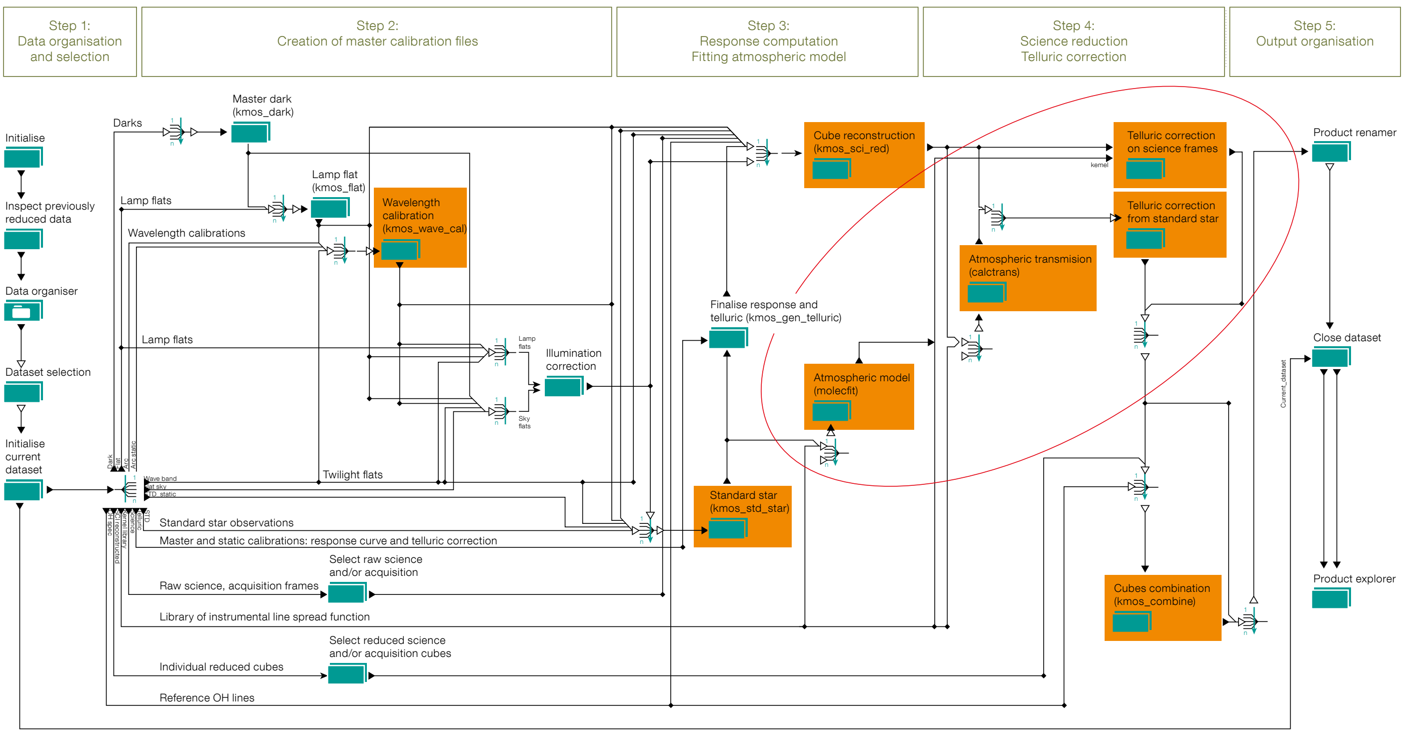


Figure 4. Schematic representation of the two molecfit strategies implemented in the KMOS EsoReflex workflow. The default molecfit on-standard approach (on the left) obtains atmospheric parameters from a telluric standard observation before computing the atmospheric transmission at the airmass and spectral resolution of the scientific exposure. In the molecfit on-science approach (on the right), the process is applied directly to the science exposures.

Figure 5 (below). The EsoReflex KMOS workflow. Each green box represents a step in the data reduction chain. Orange boxes identify interactive components in which the user has the opportunity to inspect the products of that specific step and re-run the corresponding recipe with different parameters. Interactive modules that are specific to telluric correction are marked by the red ellipse. User-defined scripts can be plugged into the workflow as well.



wavelength regions and the reference spectra to fit the atmosphere, which are fundamental steps in the on-science approach. An EsoReflex tutorial[5] (Coccato et al., 2019) that guides the user through the data reduction and an updated pipeline manual are available at the ESO instrument pipelines webpage[6].

The on-standard molecfit approach is used for the in-house ESO reduction of KMOS observations for the ESO archive; these reduced data products will be available to the astronomical community soon through the ESO archive science portal[7]. Improvements with respect to this method can be obtained case by case with the on-science molecfit approach. Indeed, this approach limits the differences in the molecule column densities between the scientific spectrum and the target spectrum that arise simply by looking at different locations on the sky (despite closeness in time or airmass). The on-science method, however, requires interactive selection of bright science spectra to use as references, and a careful selection of the wavelength ranges to fit. For those reasons it is not used for the archive products. In future, the molecfit tools will be integrated into all the near- and mid-infrared instrument pipelines and workflows to grant the user flexibility to perform telluric correction in the most efficient way.

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Kausch, W. et al. 2015, A&A, 576, 78
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Links

[1] Atmospheric & Environmental Research (AER) Radiative Transfer Working Group Website: http://rtweb.aer.com/
[2] HITRAN database: https://hitran.org/home/
[3] National Centers for Environmental Information Global Data Assimilation System (GDAS): https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-data-assimilation-system-gdas
[4] ESA Michelson Interferometer for Passive Atmospheric Sounding: https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat/instruments/mipas
[5] The Reflex KMOS tutorial (Coccato et al. 2019) can be downloaded from the following link: http://www.eso.org/sci/software/pipelines/
[6] VLT instrument pipelines: http://www.eso.org/sci/software/pipelines/
[7] ESO Science Archive Portal: http://archive.eso.org/scienceportal/

M. Cabral/ESO

The VLT/I at sunset.