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Sky subtraction for observations without plain sky information

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Abstract. In the near-IR, the sky background is dominated by highly variable airglow emission lines. This is an issue for the sky subtraction in spectra without plain sky, where reference sky spectra taken at a different time as the object spectrum are required. For this reason, we have developed the instrument-independent sky subtraction code SKYCORR, which uses physically motivated line group scaling in the reference sky spectrum by a fitting approach for an improved sky line removal in the object spectrum. Possible wavelength shifts between both spectra are corrected by fitting Chebyshev polynomials and advanced rebinning without resolution decrease. For the correction, the optimised sky line spectrum and the automatically separated sky continuum (without scaling) is subtracted from the input object spectrum. Tests show that SKYCORR performs well (per cent level residuals) for data in different wavelength regimes and of different resolution, even in the cases of relatively long time lags between the object and the reference sky spectrum. Lower quality results are mainly restricted to wavelengths not dominated by airglow lines or pseudo continua by unresolved strong emission bands.

1. Introduction

In the near-IR wavelength regime, the Earth's atmosphere mainly emits non-thermal line radiation. This so-called airglow is highly variable on different time scales. Its intensity also significantly depends on the viewing direction. Subtracting this emission from astronomical spectra can, therefore, be very challenging if 2D plain sky information is not available. In this case, it is not possible to interpolate the airglow emission at the object's position. Hence, for instrument modes only providing 1D sky information or 2D spectra without plain sky, a reasonable sky subtraction usually requires an independent reference sky spectrum taken at a very similar time and position. Such observations are expensive in terms of observing time and the quality of the sky subtraction can still be quite poor if the exposure times are long.

2. The Method

The Innsbruck group of the Austrian ESO In-Kind Project has developed the programme SKYCORR (see Figure 1; see also Kausch et al. (2013a)), which solves the sky subtraction problem by an adaption of the reference sky to the airglow emission in the science spectrum via a fitting approach. The basic idea comes from the grouping of airglow lines with similar molecular transitions, which are expected to have a comparable variability. Two types of groups were defined: *A* groups connecting lines of the same electronic/vibrational band (see Figure 2 *Left* for the near-IR OH bands) and *B* groups consisting of lines with similar rotational upper levels belonging to the same electronic band of a molecule (see Figure 2 *Right* for OH(4-2) as an example for OH bands). Then, these groups can be scaled as a whole. Outliers caused by object features, telluric absorption lines, and instrumental defects can be identified and excluded from the derivation of the scaling factors.

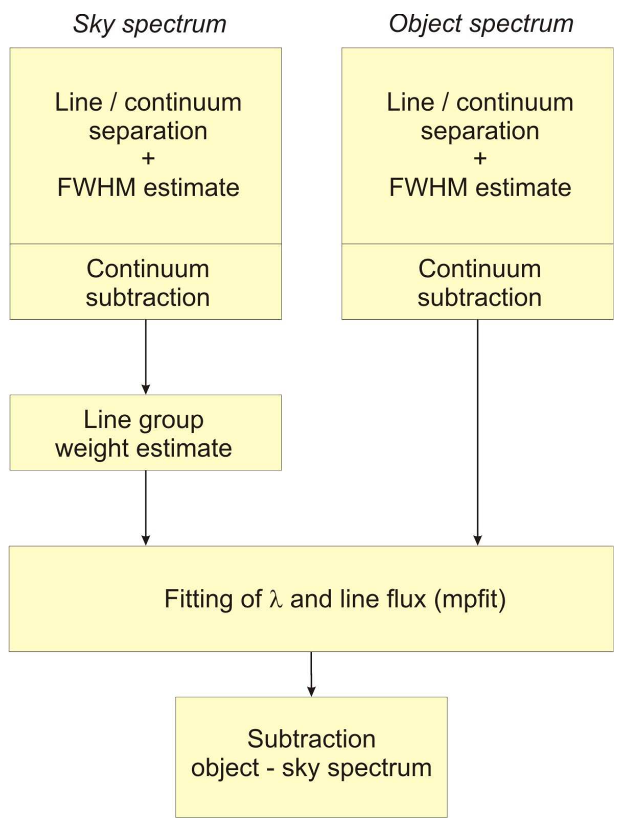

Figure 1. SKYCORR workflow

The approach is related to the method of Davies (2007) optimised for the VLT SINFONI pipeline, but ours is instrument independent and more sophisticated. The scaling factors are estimated for each pixel (instead of using fixed wavelength ranges) based on a comprehensive airglow model that we have developed for Cerro Paranal (Noll et al. 2012). This model also extends the SKYCORR applicability to the optical regime. For the fitting, the Levenberg-Marquardt χ^2-minimisation algorithm implemented in the MPFIT package of C. Markwardt[1] is used. Small differences in the wavelength grids of the reference sky and science spectra can be corrected by fitting Chebyshev polynomials and advanced rebinning without resolution decrease. Sky continua are separated from the airglow lines before scaling via a line finder and an airglow

[1]http://www.physics.wisc.edu/~craigm/idl/cmpfit.html

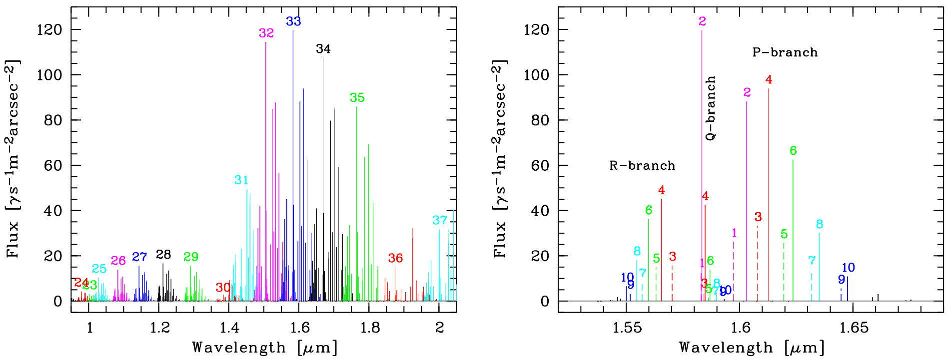

Figure 2. Examples of SKYCORR line groups for airglow scaling. *Left:* Numbered *A* groups of OH ro-vibrational bands in the near-IR. *Right:* *B* groups of OH rotational transitions illustrated for *A* group 33, i.e. the OH(4-2) band.

line list (Noll et al. 2012), and subsequent continuum interpolation. Sky continua cannot be scaled, since it is not possible to disentangle the sky and object continuum contributions. At least for the near-IR regime, this is not a major issue due to the faintness of the sky continuum components. The final sky-corrected object spectrum is calculated by subtracting the scaled and shifted sky lines and the unscaled but shifted sky continuum of the reference sky spectrum from the input object spectrum.

3. Results

We have performed tests of SKYCORR for different low- to medium-resolution ESO VLT instruments (FORS, SINFONI, X-Shooter) covering the wavelength regime from the near-UV to the *K*-band. In general, the sky subtraction works well with line residuals reaching the per cent level only. This is illustrated by Figure 3, which shows the sky subtraction results for a medium-resolution near-IR X-Shooter spectrum of a star corrected by means of two sky spectra taken at the same time and 2 h later, respectively. The former was actually extracted from the 2D spectrum also including the object. In this way, the performance of SKYCORR could be compared to the standard 2D sky interpolation method. The results are very similar, even though SKYCORR has only 1D information for the correction. The main purpose of SKYCORR is to correct object spectra with sky spectra taken independently. Figure 3 shows that the sky subtraction residuals tend to be significantly stronger for the example with a relatively long time difference of 2 h. However, this is still about one order of magnitude better than the results for simple sky subtraction without optimisation. The sky correction results with the lowest quality are usually found for wavelength ranges dominated by the unscaled sky continuum (like the *K*-band). Moreover, extended pseudo continua by unresolved airglow emission bands can cause problems because of the unknown underlying object continuum. An example is the O_2 band at 1.27 μm in Figure 3.

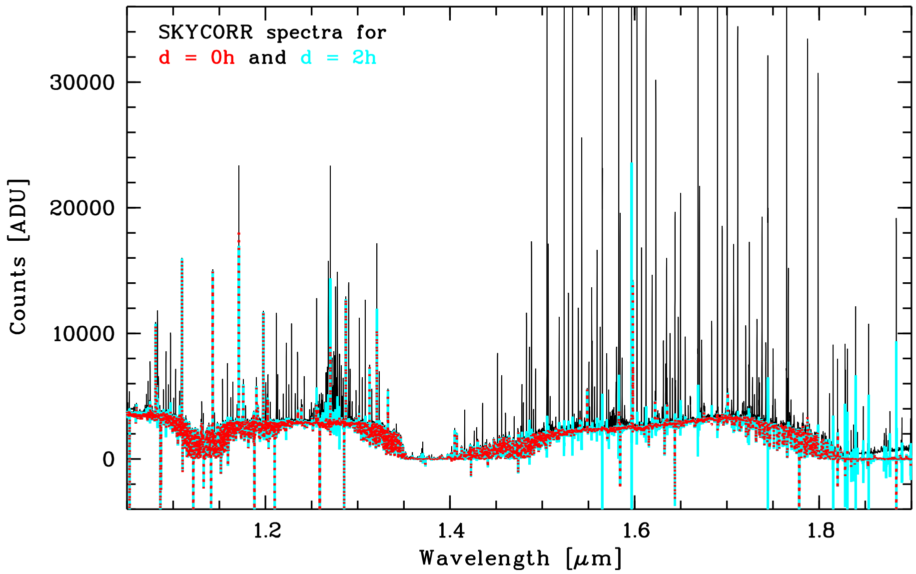

Figure 3. SKYCORR-corrected VLT X-Shooter examples (only J and H band shown): *solid black:* input science spectrum, *dotted red:* correction for sky spectrum derived from the same 2D spectrum, *solid cyan:* correction for sky spectrum taken 2 h after the science spectrum. The relatively strong, uncorrected peaks are caused by bad pixels. The regions of high line density originate from water vapour absorption bands (not corrected by SKYCORR, but see Kausch et al. (2013b)).

4. Conclusions

The SKYCORR sky subtraction in spectra without plain sky information by means of independent sky spectra promises significantly reduced airglow line residuals compared to a correction without optimisation. For near-IR data, the application of SKYCORR could help to relax the constraints for plain sky observations and, hence, contribute to a more efficient use of expensive observing time at large telescopes.

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