Rectifying Échelle Spectra – a Comparison between UVES, FEROS and FOCES

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1 Why we need well-rectified spectra

In many fields of astrophysics which make extensive use of spectroscopy the interactive placement of the continuum level is a step in the analysis which precedes the determination of physical entities (e.g. abundances). In reality, these entities are therefore not free of subjectivity, even if automated procedures are used for the profile analysis. As a matter of fact, when broad spectral features (e.g. Balmer profiles) or regions of high line density (as found in DLAs) are under investigation only the *combined* determination of the continuum position and the quantity of interest is possible.
In an effort to attain the highest possible precision, we cannot simply pick individual spectral features and avoid ones which are demanding observationally and/or theoretically. Rather, we will have to begin to synthesize large spectral regions as a whole. For this purpose, modern échelle spectrographs are ideally suited, since they usually allow for complete optical coverage in a single exposure.
When it comes to the run of the continuum within an order and from order to order *after blaze correction*, one expects residuals reflecting the ratio of object temperature to flatfield lamp temperature, in other words only higher order terms which are a slowly varying function of wavelength. A prerequisite for this behaviour to actually occur is an optical design which secures *identical* light paths for the object light and that coming from the calibration lamp.
Unfortunately, this theoretical expectation is not always met by present-day spectrographs, as is shown below.

2 The comparison: BD $-4°$ 3208

Hα of BD $-4°$ 3208 may serve as a test case to check the *inner-order* and *order-to-order residuals* of the three spectrographs: this star is relatively bright ($m_{\rm V} \sim 10^m$) which means that it can be observed even with smallish telescopes (e.g. ESO 1.52m). In addition, it is very metal-poor ([Fe/H]~ -2.4) making it easy to locate the continuum between the low number of stellar spectral features in the orders surrounding Hα (below 10 per 100 Å!).
We have aquired spectra of this halo star with the three spectrographs FOCES, FEROS and UVES the rectification of which is discussed below.

3 FOCES – Échelle Rectification at its Best

FOCES (Fibre Optics Cassegrain Échelle Spectrograph, cf. [1]) has been mounted to the 2.2m telescope on Calar Alto in Andalucia/Spain since 1995. Its resolving power can be chosen between 40 000 and 60 000.
The spectrum presented here is the result of a coaddition of three exposures totalling 2h integration time achieving a S/N of 200 in the red. It was reduced using the FOCES pipeline software written in IDL© which takes care of all standard steps: bias and background subtraction, flatfield divison (the so-called *blaze correction*) and wavelength calibration via a ThAr exposure.
Fig. 1 shows the rectification curves (RCs) of orders 58 and 62 (two orders blue and red of Hα) superimposed on the spectrum. These RCs were defined interactively by specifying four continuum points. The divison RC(58)/RC(62) deviates from unity by less than 0.5 % allowing a rectification of the three orders containing Hα good to this accuracy. In the F & G star regime, this uncertainty contributes less than 50 K to the error budget of Balmer temperatures.
As far as the order-to-order residuals blue of Hα are concerned, a very steady behaviour is found as well: it is possible to take an RC from one order and apply it to any of the adjacent ones.

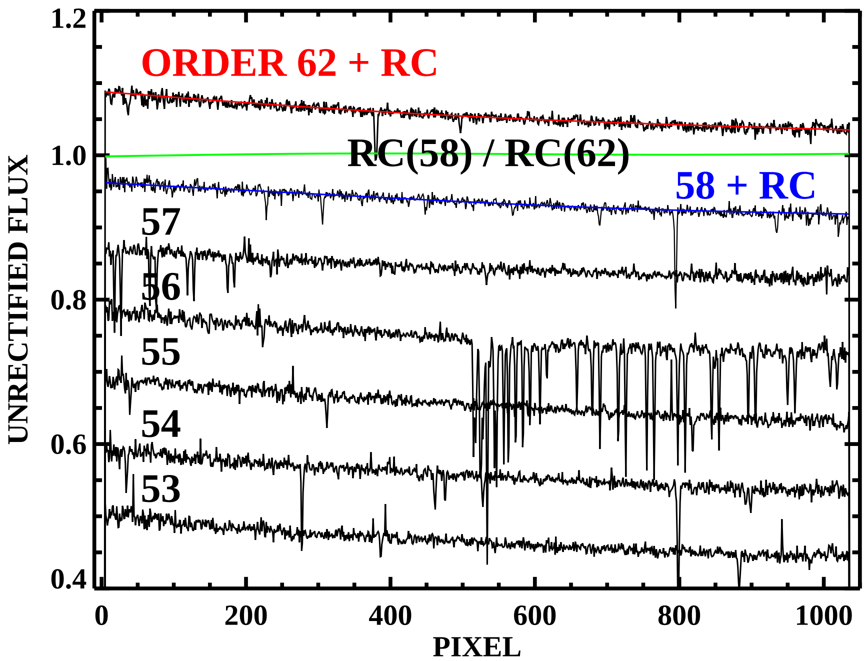

Fig. 1. The rectification of FOCES: owing to the optical design both inner-order and order-to order residuals are low allowing the rectification of Hα to better than 0.5 %

4 FEROS

The FEROS spectrograph (Fibre Extended Range Optical Spectrograph, cf. [2]) was installed on the ESO 1.52m (La Silla) in 1998. The optical design is similar to FOCES with the entrance slit being replaced by an image slicer. The resolving power is fixed at 48 000. We present the FEROS pipeline result of a 1h exposure obtained during commissioning (January 1999).
One important difference in setup is the spectral coverage per order: whereas both FOCES and UVES orders cover some 80 Å, the FEROS orders span over 200 Å. Therefore the blue edge of order 27 corresponds that of order 53 of FOCES (8 of UVES). Unfortunately, Hα is placed to the edges of orders 29 and 30 preventing an interpolation across orders containing merely the pseudo continuum of the wings. Instead, one has to define the inner-order RCs for these orders and merge them directly. Approximating the RCs for orders 29 and 30 by straight lines, this procedure works reasonably well.
The order-to-order behaviour of the residuals is less convincing (cf. Fig. 2). It might be caused either by non-identical light paths within the spectrograph (cf. Sect. 1) or by an insufficient treatment of the scattered light in the reduction.

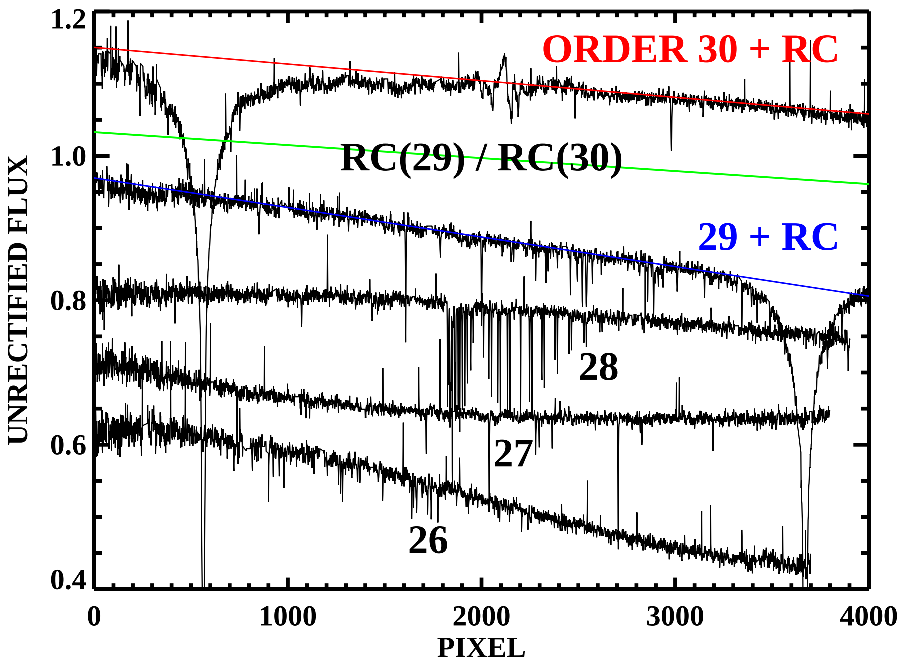

Fig. 2. The rectification of FEROS: while for orders 29 and 30 the inner-order residuals can be approximated by straight lines, those of 28 through 26 require concave/convex/sinusoidal RCs. Interpolation across orders is therefore not possible

5 UVES

In contrast to FEROS and FOCES, UVES (on Kueyen since 1999, cf. [3]) is not a fiber-linked spectrograph. This makes a fair comparison between the three spectrographs difficult. In spite of this, we include an 18min exposure of our reference star to see how accurately Hα can be rectified using this spectrograph. We note that Balmer profile temperatures have already been derived from UVES spectra for metal-poor stars (e.g. [4] and [5]).
The UVES reduction pipeline of period 67 yields "quick-look" spectra which are insufficient in terms of the order merging (cf. Fig. 4): broad spectral features like Hα cannot be used for plasma-diagnostic purposes. (Apparently, the technical difficulties have been overcome in the meantime [6].) Below we present orders reduced with the FOCES software EDRS (échelle data reduction softare).
Similar to orders 29 and 30 of FEROS, the inner-order residuals can be well-approximated by straight lines. More problematic is the non-monotonic run of the order-to-order residuals: the use of one RC on a different order is not advisable. Nevertheless, a reliable rectification of Hα via interpolation seems feasible, if the merging is done carefully.

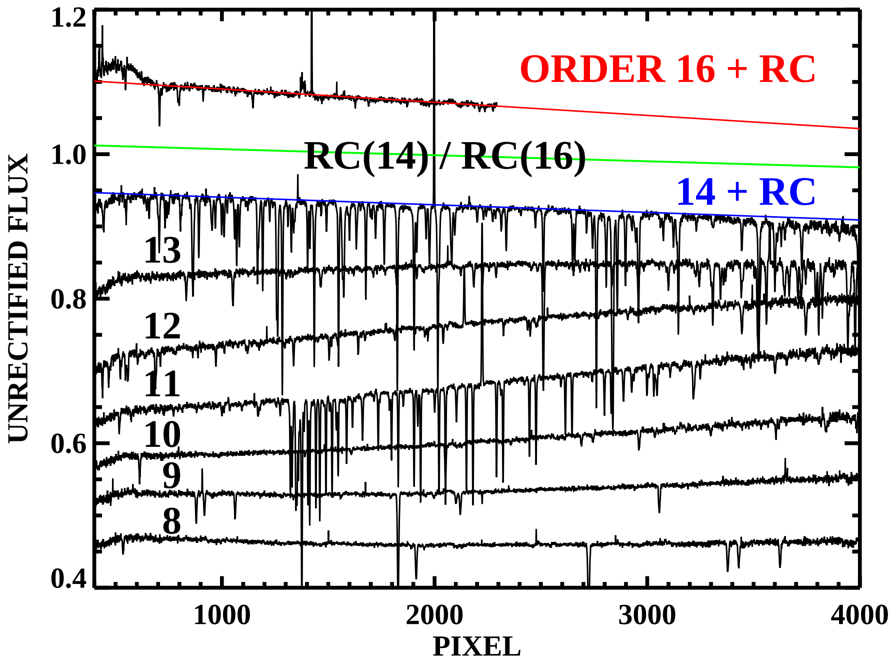

Fig. 3. The rectification of UVES: inner-order residuals are remarkably low (disregarding the bluest 500 pixels), yet a non-monotonic behaviour of the order-to-order residuals is found

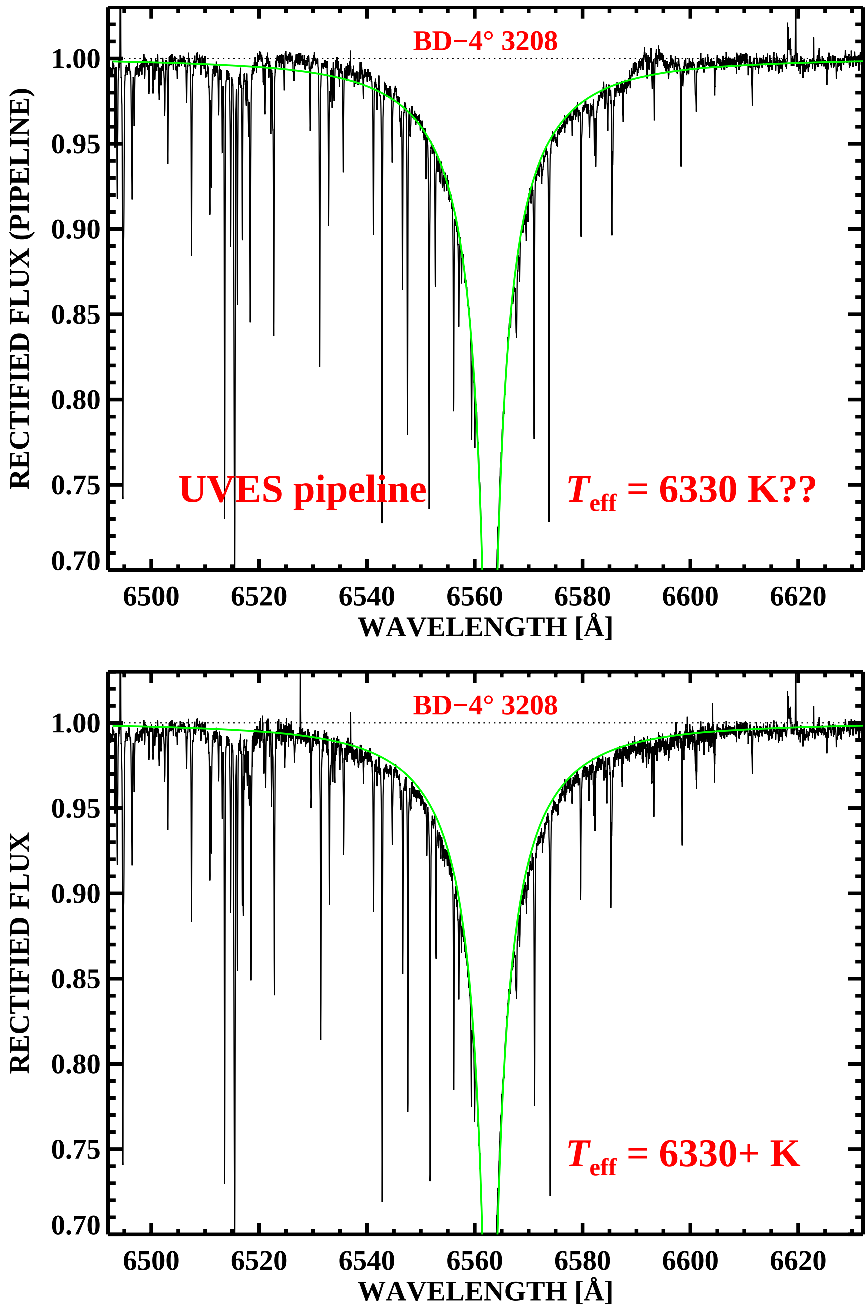

Fig. 4. Direct comparison between the P67 pipeline result and a reduction based on the FOCES software EDRS. The best estimate for the effective temperature as derived from FOCES spectra ($T_{\rm eff} = 6330$ K) is nearly recovered by our reduction procedure

Table 1. Rectification qualities of the three spectrographs

spectrograph	FOCES	FEROS	UVES
fibre-linked	yes	yes	no
inner-order	++	−	++
order-to-order	+	∘	∘

6 Conclusion

Table 1 summarizes the rectification qualities of the three spectrographs discussed above. The most astonishing result is the fact that UVES can rival the fibre-linked spectrographs when it comes to inner-order residuals.
We make the following recommendations for current and future instrumentation (and issues related to the data reduction) of the VLT/VLTI:

- From the point of view of spectrograph design, more weight ought to be given to minimizing inner-order and order-to-order residual for next-generation échelle specrographs (like e.g. AVES presented at this conference).
- For standard settings, order spectra ought to be supplied alongside the merged spectra and raw data. (Initially, a *science* reduction pipeline was a Level 1 requirement for the VLT which was subsequently dropped for most instruments, yet in reality a good portion of the publications from the VLT community is based on the supplied “quick-look” spectra.)
- For best exploitability the VLT archive ought to contain both the order and “quick-look” spectra.

The impact of point 1 above can be appreciated by looking at [7]: the spectroscopic results of Fuhrmann would be inconceivable without a spectrograph having rectification qualities which match those of FOCES.

References

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