Merging of Spectral Orders from Fiber Echelle Spectrographs

Petr Škoda

Astronomical Institute of the Academy of Sciences of the Czech Republic

Herman Hensberge

Royal Observatory of Belgium

Abstract

We have reviewed the data reduction of two fiber-based echelle spectrographs (HEROS and FEROS) with emphasis on similarities of the inconsistencies between the overlap of spectral orders before merging.

The literature on echelle data reduction shows that such inconsistencies are commonly observed (and usually handled by rather heuristic procedures - mostly interactively).

For both instruments, it seems to be the calibration unit which introduces through the flat fielding the major part of the problems. We discuss strategies to treat the problems and to remove the inconsistencies before merging the spectral orders with a minimum of interactive, subjective algorithms.

1 Introduction

Merging spectral orders from echelle spectra is known to be non-trivial. Some manual of echelle spectroscopy even advise against trying it. Authors, who do the merging, usually report problems and try to solve the order inconsistencies by some heuristic interactive methods (Churchill 1994, Hall et all. 1994, Erspamer and North 2002). Last year, De Cuyper and Hensberge (2002) commented on a study of calibration flat-fields taken with the FEROS fiber-fed echelle spectrograph at ESO and pointed out several effects influencing the merging. In this contribution, we present the results of an extended analysis including special calibration flat-fields, dome flat-fields and science exposures of bright objects. The results obtained from FEROS were compared, where possible, to red-channel exposures made with HEROS at Ondřejov Observatory.

2 Spectrographs

A detailed description of both instruments can be found on WWW pages of FEROS[1] and HEROS[2] respectively. FEROS is a 2-fiber spectrograph covering a wide spectral region (3600 – 9000 Å) in 39 spectral orders. It is particularly suited to distinguish effects which are related to blazed spectral orders from optical projection effects since the bluest spectral orders are much narrower than the size of the detector while the reddest orders are covered over a bit less than their free spectral range. FEROS operates in a temperature and humidity—controlled room. HEROS is a one-fiber instrument developed earlier by the same team in Heidelberg, as a compact echelle spectrograph which has been used at several telescopes. Now it has been connected for more than two years to the 2m telescope of Ondřejov observatory. The light from the telescope Cassegrain focus is fed by the 10m long fiber to the echelle grating and than after the beam-splitter goes to two independent channels : blue (3600 – 5600 Å in 70 orders) and red (5800 – 8400 Å in 32 orders).

2.1 Experiences with FEROS

The projection of the spectral orders on the detector over an observing run of 4 nights was stable in the wavelength direction on the order of 0.1 pixel (except for an explained, and meanwhile removed oscillation, due to short-term temperature fluctuations of 1 K in the FEROS room) and in the spatial (cross-order) direction on the order of 0.5 pixel (Fig. 1).

However, the position of the blaze profile in wavelength changed on the order of 10 pixels (i.e. 10^{-4} of the wavelength) in a highly correlated way with the changes in spatial direction (Fig. 1). These slow temporal changes apply as well to calibration unit flat-fields as to dome flat-fields or scientific exposures. Such changes, if not taken into account when flat-fielding a science frame, lead to inconsistencies on the level of several percent of the flux in the overlap of spectral orders (Fig. 3 and Fig 4).

The shift in pixel units is comparable in all orders (compare Fig. 4 and Fig. 5) and leads to important overlap inconsistencies where the blaze function is steep.

After a major maintenance mission at ESO, the spectral orders were positioned still as earlier, but the blaze functions had changed their shape (width) such that "shifted" old profiles would not serve any longer to prevent overlap mismatch. A major change made during the maintenance was the improvement of the centering of the light bundles from both flat-field calibration lamps such that they illuminate the fiber(s) in the same way.

In 2001 and at the start of our observing run in 2002, unblazed calibration flat-fields showed an oscillatory pattern in wavelength (Fig. 6 which is consistent in the overlap of subsequent orders. The period of the pattern is similar to the free spectral range, but varies as wavelength square rather than proportional to wavelength as in the case for the free spectral range. The amplitude depends strongly on wavelength and can be quite different in the two fibers. After an intervention of A. Kaufer in the calibration unit, the oscillations were strongly damped and basically at the limit of detectability, but it was not understood why. After ESO's maintenance mission, they were still absent. More important, oscillations were never present in dome flat-fields or science frames and hence can be identified from comparison to high signal-to-noise dome flat-fields. Hence, the origin of the oscillations is linked to the calibration unit. It uses the light of two tungsten lamps operated at a different voltage to get one of them five times brighter, with the red light of the brighter lamp blocked by a combination of filters such that their combined light output is relatively constant over the large wavelength range spanned by the instrument.

[1] http://www.ls.eso.org/lasilla/Telescopes/2p2T/E1p5M/FEROS/index.html
[2] http://www.lsw.uni-heidelberg.de/projects/instrumentation/Heros

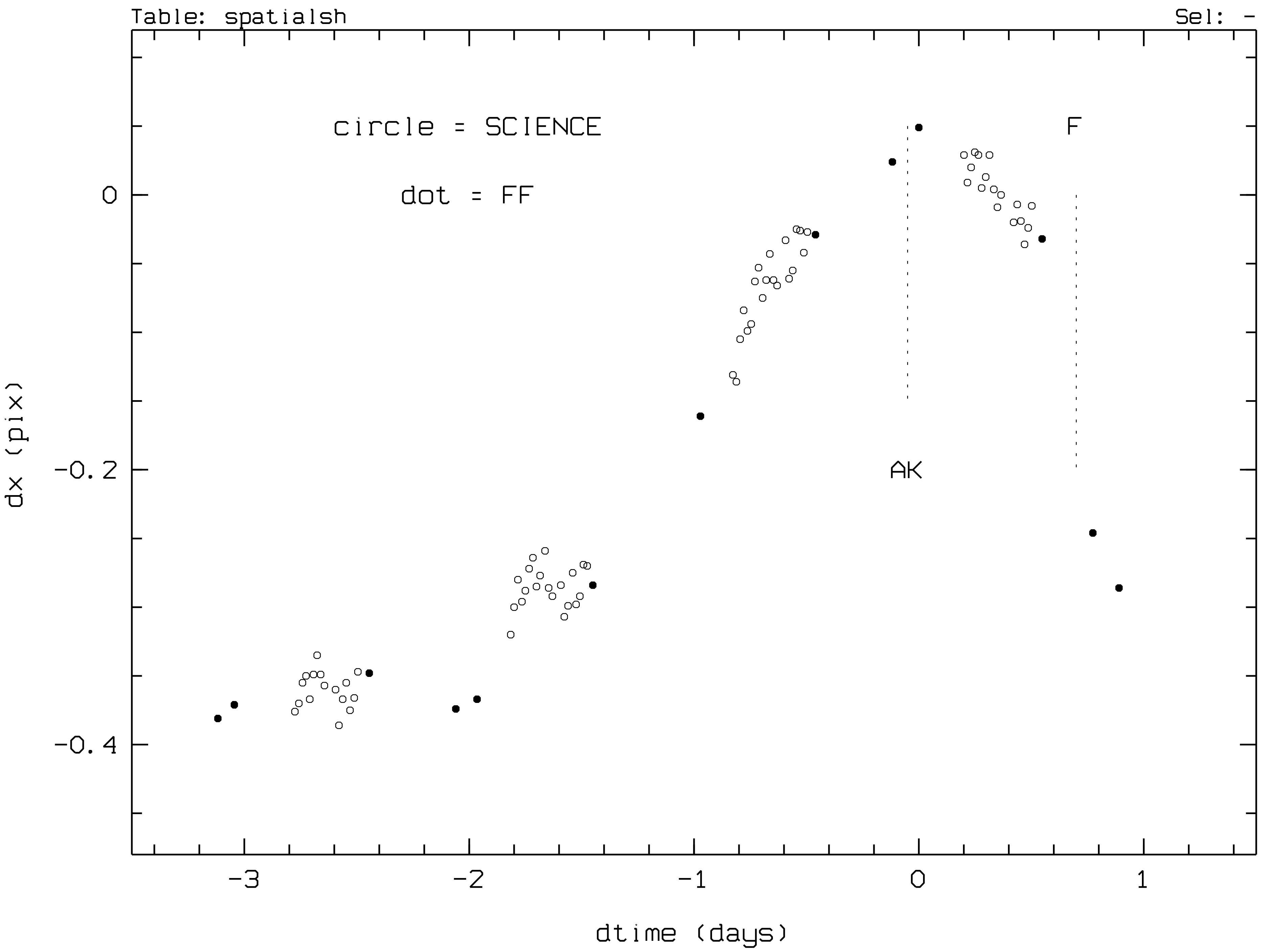

Figure 1: FEROS, time evolution of the position of the spectral orders (expressed as a differential shift in pixel space, in cross-order direction, relative to a standard frame) during an observing run. Flat-field images (+) and science frames (o) are indicated with different symbols. during an observing run.

2.2 Experiences with HEROS

Temporal changes in the blaze profile are detected on shorter time-scales, which is presumably related to the spectrograph operating in the dome rather than in a controlled room. The changes vary smoothly over subsequent orders, but cannot be represented by a simple small shift in wavelength of the blaze function. This may be related to the fact that the blaze profiles produced by HEROS are not so near to the theoretical predictions than in the case of FEROS: the blaze profiles of different spectral orders are almost identical when expressed in the coordinate

$$\frac{\nu}{2\pi} = \frac{m}{2}\left(\frac{\lambda_b(m)}{\lambda} - 1\right)$$

(where m refers to the spectral order, λ to the wavelength and $\lambda_b(m)$ to λ in order m at the peak of the blaze intensity, see also De Cuyper & Hensberge, 2002) in the case of FEROS; but shape and width does not scale accurately in that way for HEROS.

Since flat-fields are taken commonly with each science exposure at Ondřejov (because of the fast low-frequency temporal changes of the calibration images), efforts to address the order merging problems were directed to the study of the unblazed science frames rather than considering the calibration images and the science frames separately, as in the FEROS case.

In order to visualize the lack of consistency in the order overlap regions more clearly, we present figures wherein the global wavelength dependency of instrument and object is removed from the separate orders - a step which in a real data reduction chain is the ultimate one i.e. the normalisation of the merged spectrum.

Fig. 7 shows the separate spectral orders and the level of inconsistency in the regions of spectral order overlap. Overplotted is a "correction function" with identical shape (in pixel space) in all 32 spectral orders, but smoothly varying amplitude. Dividing by this function produces the consistent separate orders shown in Fig. 8.

Since only few frames were studied at present, we can make no comments on temporal variability of this correction function. However, it is clear that overlap inconsistencies can be removed in principle in a robust way.

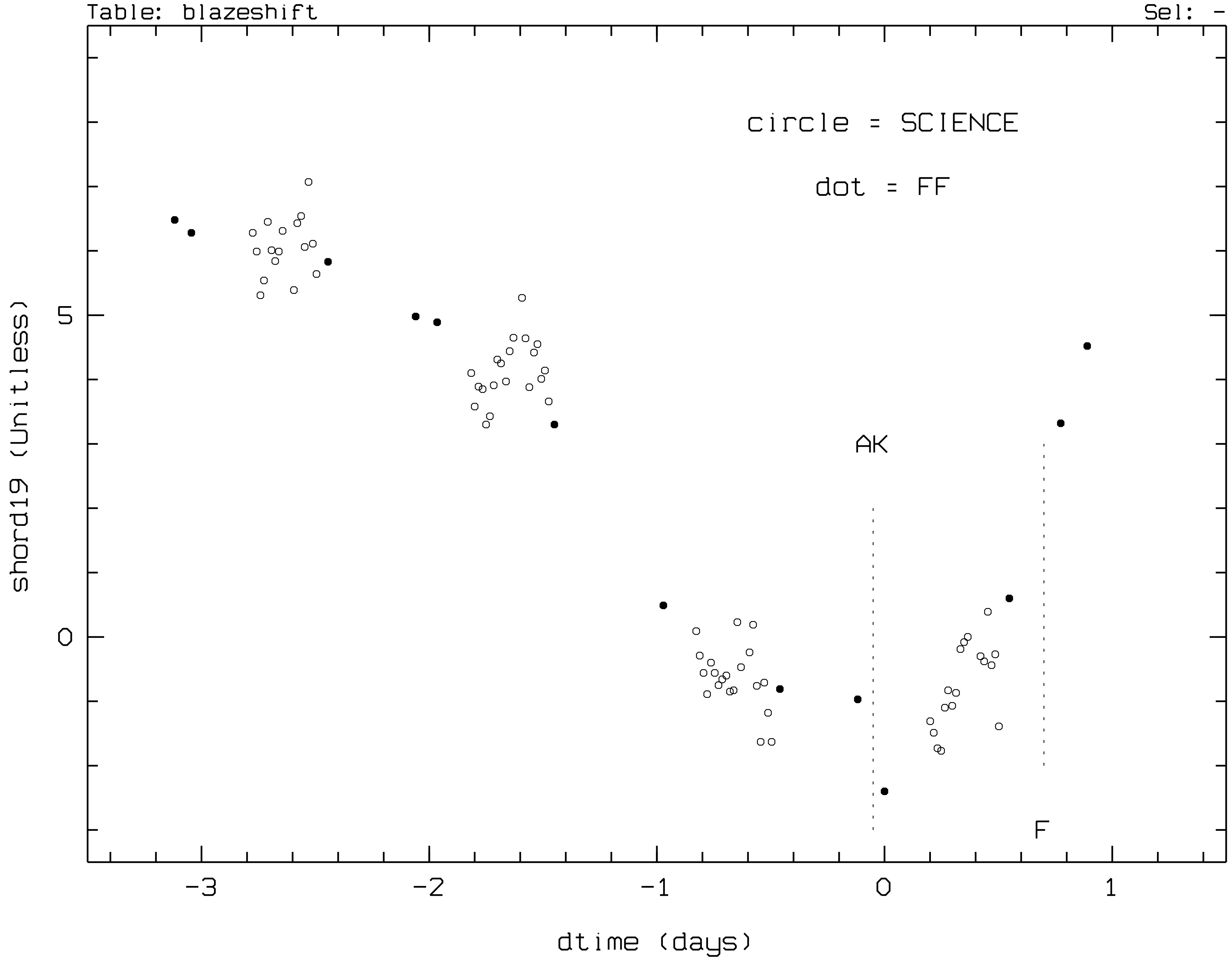

Figure 2: FEROS, time evolution of the shift of the blaze function along the spectral order (in pixel units). Note the correlation with Fig. 1

3 Conclusion

The analysis of data obtained by the fiber echelle spectrographs FEROS at ESO, La Silla and HEROS at Ondřejov, Czech Republic, identifies the high sensitivity of the shape and position of the blaze function as the primary source of order overlap inconsistencies. Since the changes in the blaze function are very consistent over many spectral orders, and highly correlated with positional changes in the projection of the orders on the detector a robust empirical model can be developed. However, on a longer term, the origin of these effects should be understood such that action can be taken to stabilise the blaze function sufficiently.

In addition, calibration flat-fields may contain wavy low-frequency patterns in wavelength space. They are neither detectable in science spectra or dome flat-fields, such that high S/N dome flat-fields can be used to detect and remove them.

In the case that sufficient attention is paid to understand the calibration unit, in order not to introduce spurious low-frequency patterns in the flat-fielded science data, merging spectral orders becomes a trivial exercise.

4 References

Churchill, C.W. 1994, Lick Obs. Techn. Rep. No 74
De Cuyper J.P., Hensberge H. 2002, ADASS XI, in press
Erspamer, D. and North, P. 2002 A&A 383, 227
Hall, J.C., Fultoni, E.E, Huenemoerder, D.P., Welty, A.D. and Neff, J.E. 1994, P.A.S.P. 106, 315

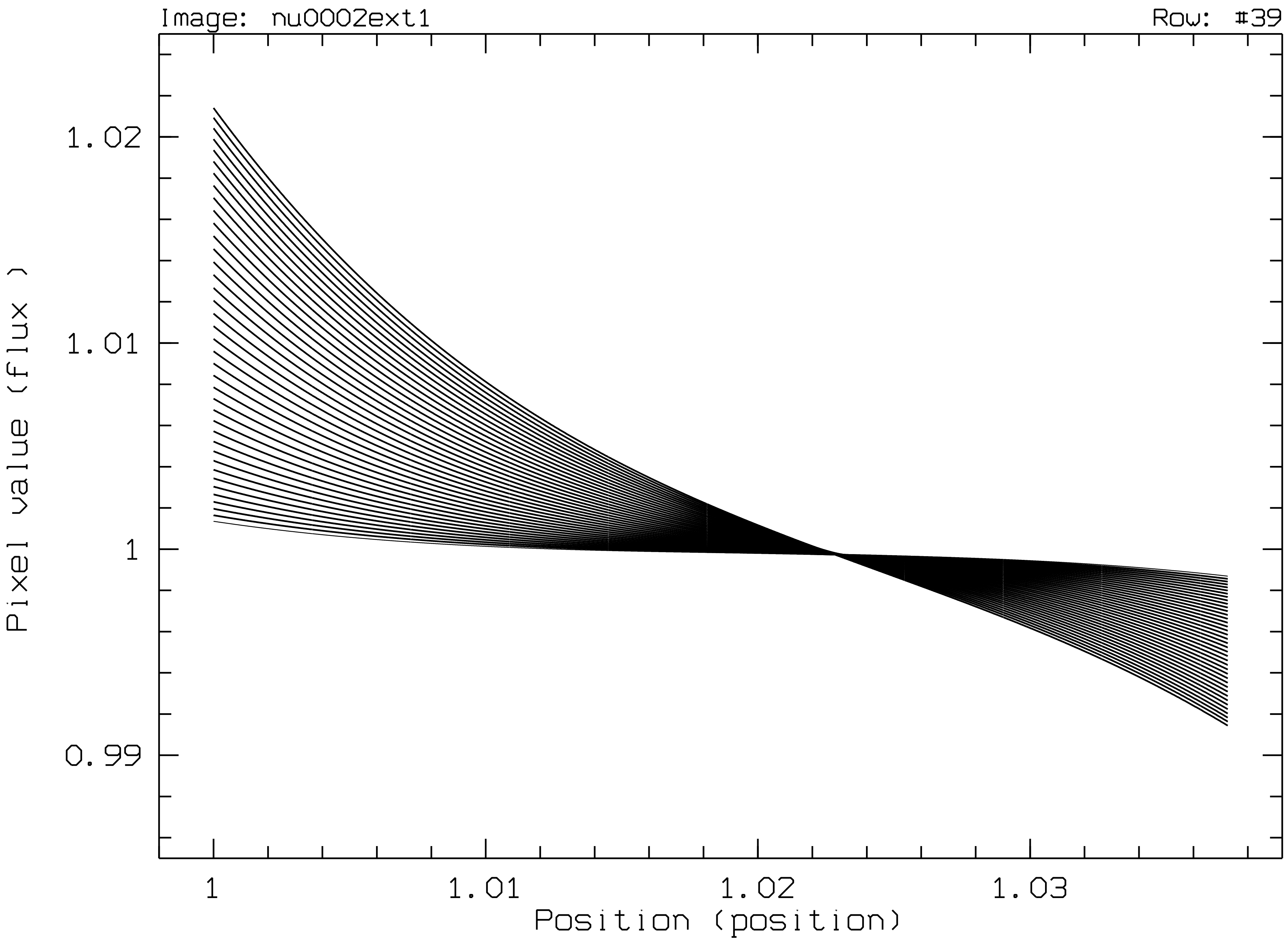

Figure 3: FEROS, the ratio of extracted orders when unblazed with a flat-field, or with the same flat-field wherein the blaze profile is shifted by two pixels. 39 spectral orders are shown, the more inclined ones are the bluer ones, which have increasingly smaller free blaze profiles relative to the detector size. Note the implied inconsistencies at identical wavelengths towards the end of one order and towards the start of the next.

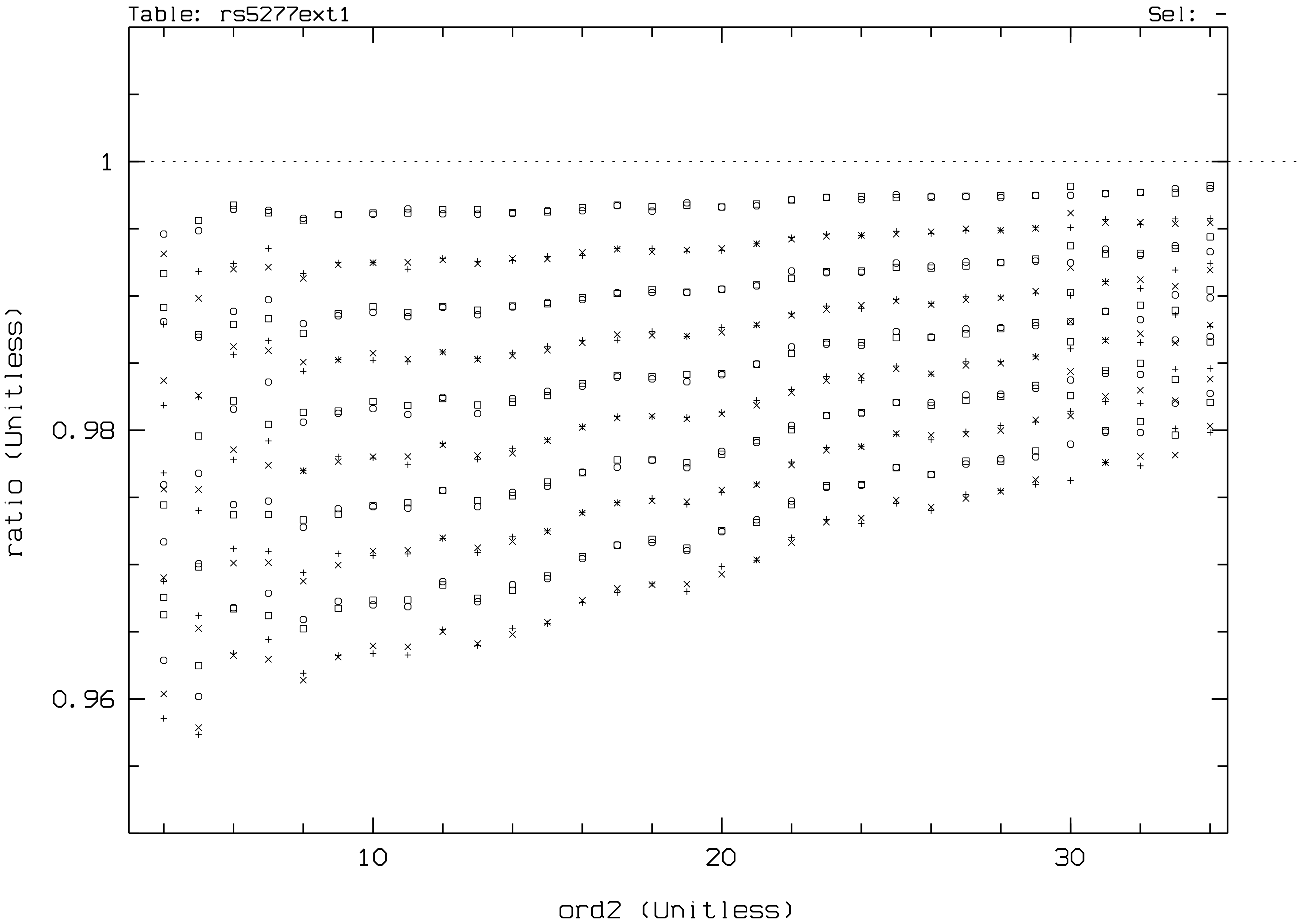

Figure 4: FEROS, the predicted ratio of fluxes in the overlap of subsequent orders. Data for different fibers are almost identical. Observed blaze profiles and spectral order overlap are taken into account. Blue orders are at the left, red spectral orders at the right. Data are given for shifts of the blaze function of 1, 2, .. , 10 pixels and for the two fibers (different symbols).

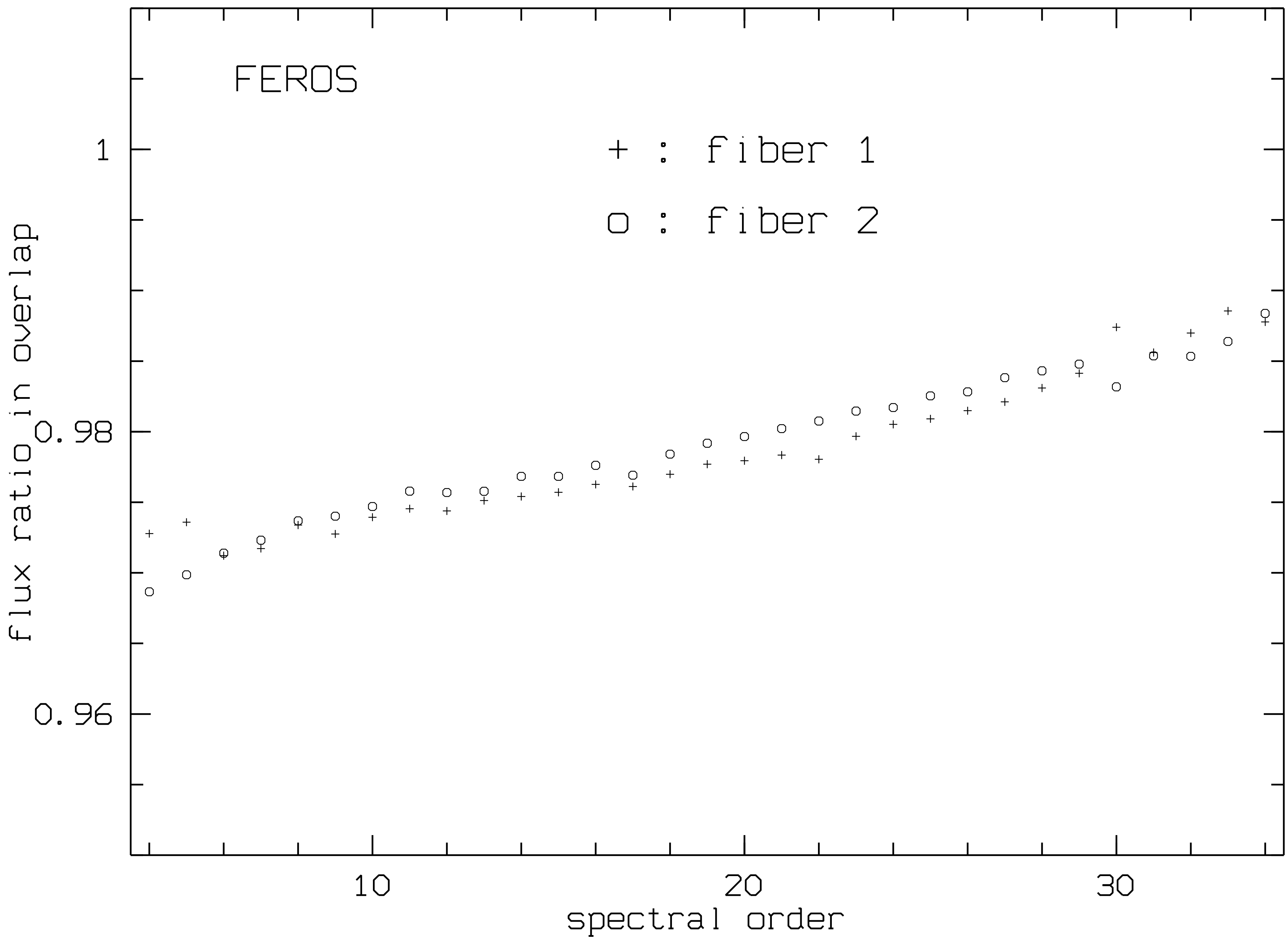

Figure 5: FEROS, the observed ratio of fluxes in the overlap of subsequent orders for a specific couple of flat-field frames and the two fibers. Note the similarity with fig. 4 suggesting a very similar shift of the blaze function in all orders.

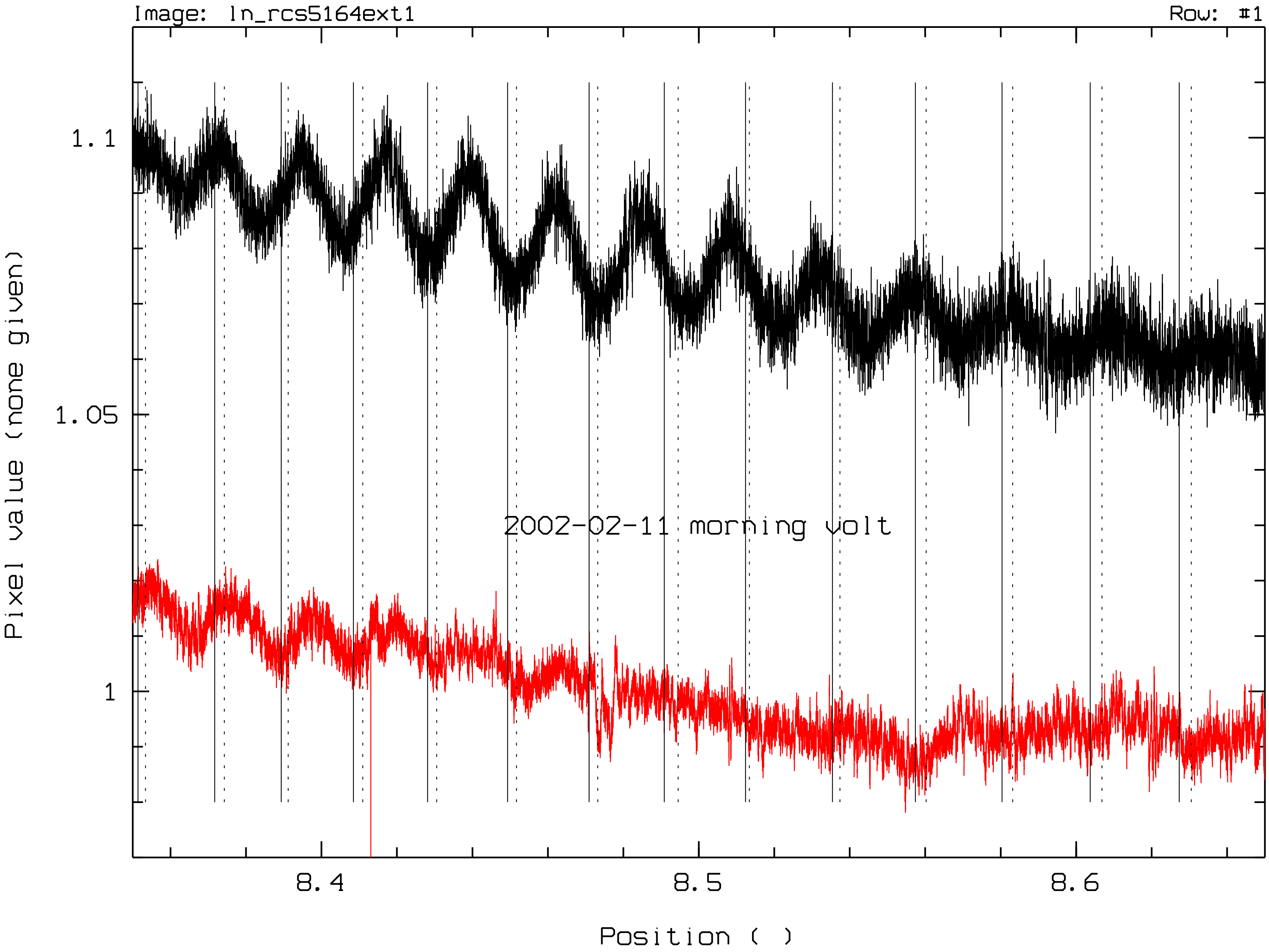

Figure 6: FEROS, the oscillation pattern as observed in a flat-field images unblazed with a flat-field taken when the pattern had insignificant amplitude. Black and red refer to the different fibers. Vertical lines indicate where orders start (full line) and end (dashed line). The pattern is plotted against ln wavelength (wavelength range 4230 - 5710 A). Outside of this range the oscillation pattern is not seen.

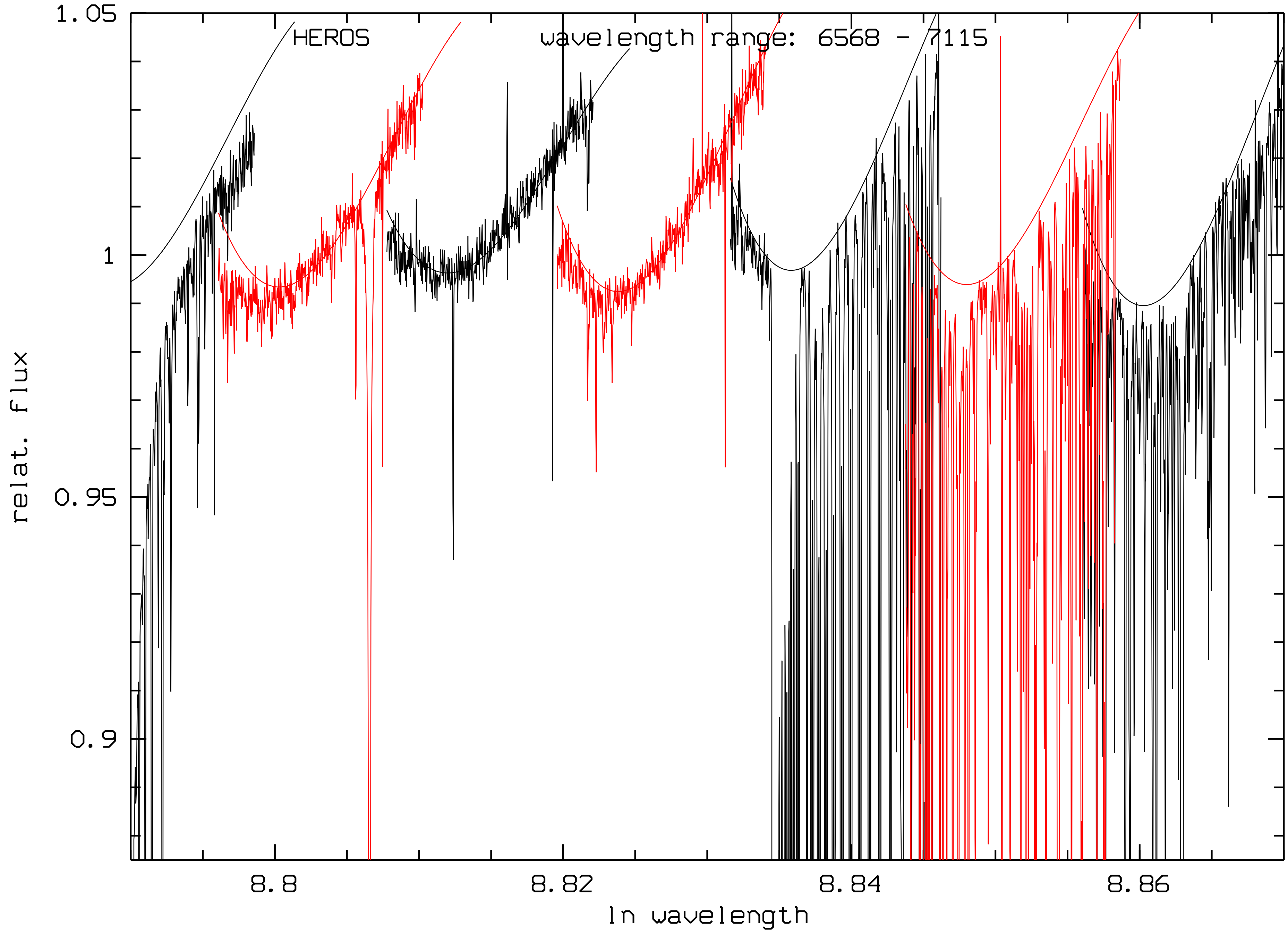

Figure 7: HEROS, 7 spectral orders starting from the longward wing of H_α. Overplotted is the function fitted to the instrumental signature, which is, except for its amplitude, identical in all orders. Subsequent orders are shown in different colors.

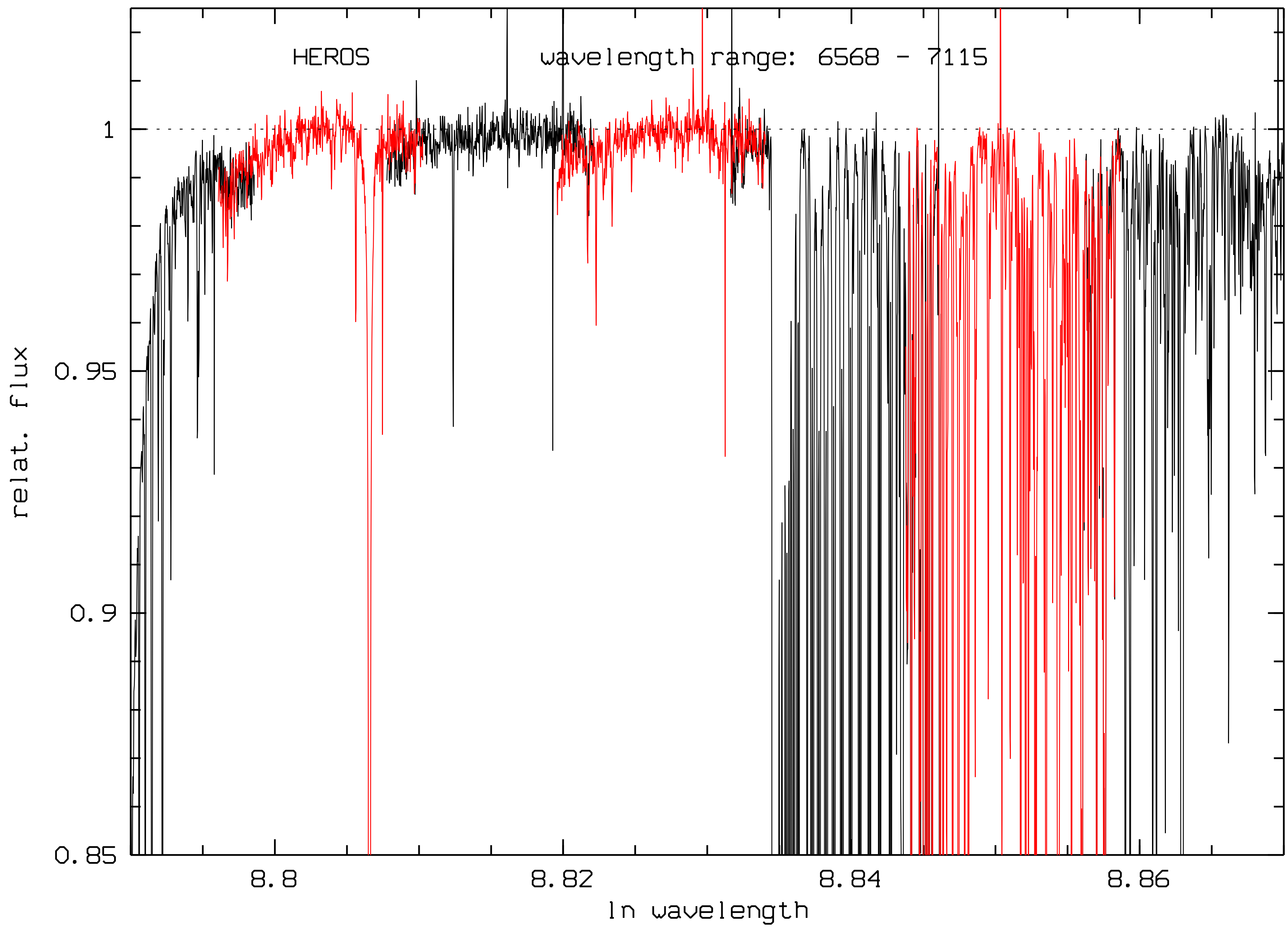

Figure 8: HEROS, same part of spectrum as in Fig. 7 after removal of the instrumental signature. Inconsistencies in the overlap of spectral orders are reduced to well below the 1% level.