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# Wavelength Calibration at Moderately High Resolution

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**Abstract.** Unrecognized blending in Thorium-Argon (Th-Ar) lamp spectra is a main contributor to calibration uncertainties. We present improved dispersion-dependent Th-Ar wavelengths for the features seen with moderate dispersion instruments.

## 1. Background

The calibration of astrophysical spectra in wavelength based on calibration lamp data suffers from different kinds of uncertainties. Besides inaccuracies in the observational phase, common data reduction practice adds "pixelation" errors, due to the fact that the centering method does not use the correct PSF. These model mismatch errors depend, for a given feature, on the sub-pixel location of the line center (David & Verschueren, private communication). In addition, there are dispersion-dependent errors, due to the fact that the laboratory input wavelengths refer to a pure line, while the features observed at astrophysical dispersions are generally blended to some extent. This aspect is the subject of our paper, with an application to Th-Ar lamps. Lastly, there is a lack of robustness by using a calibration relation with too many parameters with respect to the physics involved: echelle orders are often fitted independently, as well as sequences of spectra obtained under similar conditions (Hensberge & Verschueren 1989; Hensberge et al. 1995).

## 2. Anticipated Accuracy

Following T. M. Brown (1990), the centering accuracy for critically sampled Gaussian lines in the photon-noise limit is 0.01 pixel for lines with 3400 electrons detected in their central pixel (after extraction in cross-order direction). Usually as there are enough calibration lines available, the systematic effects on the centering and on the input data should not exceed this level. Therefore, even fairly weak blends cannot be included as calibrators without correcting their laboratory wavelength (Hensberge & Verschueren 1990). Figure 1 shows six lines, five of which are discretizations of a Gaussian PSF with $\sigma = 0.8$. One of them is actually a blend with a line having 10% of the intensity of the primary and situated one pixel to the right of the primary. The blend induces an error of 0.07 pixel compared to the wavelength of the primary line. The heavily blended lines commonly eliminated by observers correspond to substantially larger errors.

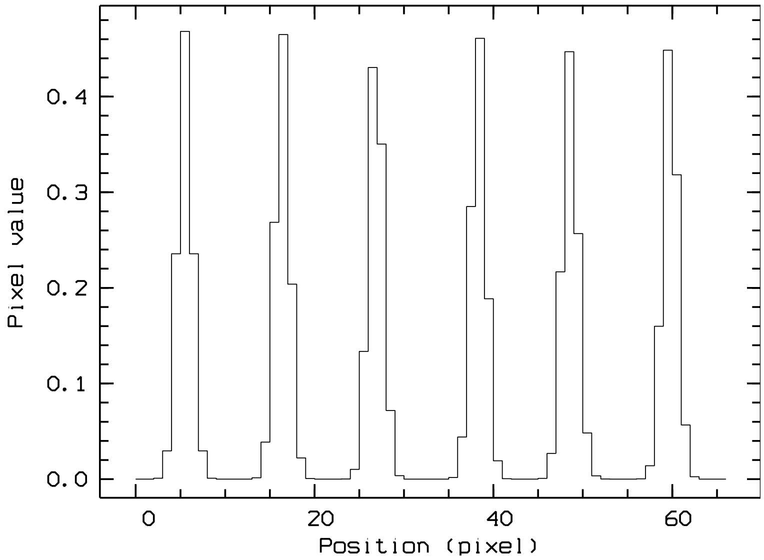


Figure 1. Shows five discretizations of a Gaussian line indistinguishable from a weak blend feature.

## 3. Selected Wavelength Calibration Lines

Unblended lines are quite scarce at moderate dispersion. However, accurate calibration points can be provided by the many weakly blended lines if their input wavelengths are corrected for blending. Computations were done at four pixel scales between $\lambda/100,000$ and lines. The laboratory spectra were broadened to the desired resolution in order to determine the dispersion-dependent input wavelength of the features. The uncertainties present are due to several factors, such as the relative line intensities, the line width, the exact centering algorithm etc., and the details of the computations are discussed in De Cuyper & Hensberge (1995).

The laboratory data were taken from Palmer et al. (1983) for Th and of Minnhagen (1973) and Norlèn (1973) for Ar. The Ar to Th line ratios used are compatible with the lamps in use at ESO The spectrum was synthesized over a seven pixel wide interval for 20 different discretizations (shifted in steps of 0.05 pixel). The centering algorithm applied fits a Gaussian + constant. Improved wavelengths were derived for the features showing small ($< 0.05$ pixel) and stable (RMS over all discretizations $< 0.015$ pixel) corrections.

## 4. Results and Availability

We have composed input line lists at four pixel scales for direct use, containing a selection of commonly detectable, useful lines and their corrected wavelengths. In addition, a list containing the complete information and an algorithm permitting interpolation to other pixel sizes is provided. (For information see the

MIDAS-KSB-ORB Home Page[1].) P. Ballester is kindly acknowledged for making these lists publicly available through the ESO facilities (see the ESO Home Page[2]).

Table 1 summarizes the acceptance statistics. Figure 2 gives an example of the useful calibrators in an order of a CASPEC spectrum. When aiming for the highest possible accuracy, it is advisable to use more stringent criteria than those set in the computations. Moreover, this costs only a few of the selected lines.

Table 1. Statistics of useful calibrators for two wavelength intervals ($\lessgtr$550 nm), including all lines and those measurable with sufficient accuracy.

| Pixel Scale | All Lab. lines | | Calibrators | |
|---|---|---|---|---|
| | Blue | Red | Blue | Red |
| 0 | 7861 | 4046 | 1759 | 976 |
| $\lambda/100\,000$ | 3470 | 2901 | 1159 | 824 |
| $\lambda/50\,000$ | 1528 | 2069 | 736 | 699 |
| $\lambda/33\,333$ | 848 | 1522 | 525 | 595 |
| $\lambda/25\,000$ | 537 | 1149 | 393 | 506 |

## 5. Conclusions and Applications

Residuals of observed line positions with respect to calibration fits are in general still dominated by erroneous assumed laboratory wavelengths even after removal of the visually apparent blends or the apparent outliers. The introduction of dispersion-dependent wavelengths for the many weakly blended features at moderately high dispersion permits one to get the residuals considerably lower, to a few hundredths of a pixel. The wavelength corrections were obtained independently from the calibration fitting procedure, in contrast to clipping algorithms applied on residuals relative to such a relation. As a consequence, we can provide more realistic input wavelengths for Th-Ar lamps from below 300 to over 1000 nm in the dispersion range of interest.

Better input data not only lead directly to more precise calibration coefficients, but also provide the opportunity to derive a more appropriate mathematical representation for the calibration relation. Adequate results can then be obtained by few-parameter fits, which in the case of echelle spectroscopy cannot be represented as bivariate polynomials. The order dependence needs to be expressed as a ratio of two linear functions of the order number (Hensberge & Verschueren 1989).

[1] http://midas.oma.be/midas-ksb-orb-homepage.html

[2] http://server.hq.eso.org/eso-homepage.html

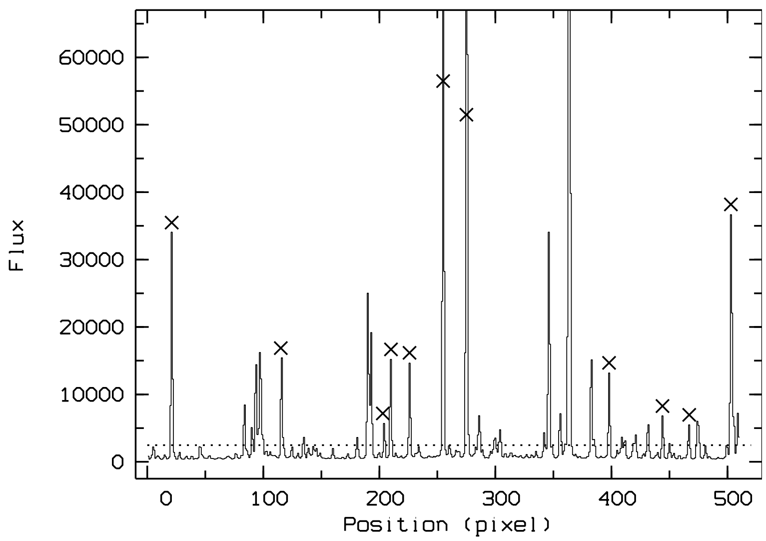


Figure 2. Shows an order (417–423 nm) from a CASPEC spectrum ($\lambda/33,333$). The useful calibrators lying above the indicated level (– – line) are marked with an x sign.

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