Spectrum Reduction

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Outline

- What is a spectrograph?
- spectrum reduction
What is a spectrograph?

- dispersive element
  - grating
  - prism
  - grism
- camera + detector

- characteristics and types of spectrographs
  - resolution: high / low
  - slit (CRIRES, UVES) / fibre-fed (HARPS, CARMENES)
  - layout (echelle)
  - single-object / multi-object / integral field spectrographs (IFS) (e.g. SINFONI)
CARMENES – Layout

- fibre-fed echelle spectrograph
- echelle diffraction grating
- cross-disperser (grism)
- triple pass of the collimator
CARMENES – Spectral Format

CARMENES echelle format (VIS)
CARMENES – Design Parameters

- pressure and temperature stabilised (vacuum tank)
- two fibres
  - fibre A: science object
  - fibre B: simultaneous calibration (RV drift or sky)

<table>
<thead>
<tr>
<th></th>
<th>VIS</th>
<th>NIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \lambda$</td>
<td>530-1050 nm</td>
<td>950-1700 nm</td>
</tr>
<tr>
<td>$R = \lambda / \Delta \lambda$</td>
<td>80,000</td>
<td>85,000</td>
</tr>
<tr>
<td>Fibre size</td>
<td>1.50 arcsec</td>
<td>1.65 arcsec</td>
</tr>
<tr>
<td>Grating</td>
<td>2 x R4 (31.6 mm$^{-1}$)</td>
<td>2 x R4 (31.6 mm$^{-1}$)</td>
</tr>
<tr>
<td>Cross disperser</td>
<td>grism</td>
<td>grism</td>
</tr>
<tr>
<td>Detector</td>
<td>e2v 231-84 (4k x 4k)</td>
<td>2 x Hawaii-2RG (4k x 2k)</td>
</tr>
</tbody>
</table>
Raw spectrum

- spectrograph images the slit to wavelength dependent positions

- Data reduction: How do we get the spectrum?
Reduction software

- IDL (REDUCE, Piskunov & Valenti, 2002)
- IRAF
  http://iraf.noao.edu/tutorials/doecslit/doecslitgif.html
- Python
- Pyraf
- ESO-MIDAS
- instrument specific pipelines
Data Reduction

- bias correction
- flat fielding
- stray light subtraction
- spectrum extraction
- wavelength calibration
- order merging
- flux calibration
Bias correction

• Bias = electronic offset (amplifier)

• bias images:
  ▶ exposure time = 0s
  ▶ regular calibration
  ▶ mean bias level
  ▶ higher order systematics
  ▶ readout noise

• master bias = average of bias images

• subtract master-bias

• measure readout noise from the count dispersion (histogram)
Bias correction

- measure mean bias level in science observations from pre-/overscan region (amplifier zero point correction)
- subtract mean (column) bias

HARPS blue CCD
Flat field

• flat lamp: featureless, smooth spectrum

• multiplicative effects
  ▶ pixel-to-pixel variations (pixel size and efficiency)
  ▶ fringing (interference pattern)
  ▶ blaze function (echelle grating)
  ▶ wavelength dependent efficiency of spectrograph (optics + detector)
  ▶ dust

• types:
  ▶ sky flat in the twilight (telluric absorption)
  ▶ dome flat
  ▶ internal flat

• master flat = average of flat frames
Flat field

- creation of a normalised flat-field (decomposition)
- set low S/N regions to 1 (noise > pixel variations)
- divide by the normalised flat-field
Flat field

- fringing in the red order

fringing in the CES spectrograph
Order and Aperture definition

- identify location and width of the spectrum (and background)
- order tracing

\[ y_{\text{cen}} = f(x, o) \]
Order and Aperture definition

Order 15: samples=486, clipped=0, degree=4

(Clayton, 1996)
Stray light correction

- global stray light (imperfection of the grating)
- local: inter-order/fibre crosstalk
- removal: polynomial/spline fit to the background regions and interpolation across the aperture
Extraction

- Quick look extraction with SAOImage ds9
Linear Extraction

- sum the raw pixel flux across the column (within the extraction width) \( s_x = \sum_y S_{x,y} \)
- simple
- \( s_x \) has not minimal variance
- extraction width?
  - too large: adding read-out noise from regions with low/no signal
  - too small: loosing signal
Optimal Extraction

- weighted extraction (Horne, 1986)

\[ s_x = \sum_y \sigma_{x,y}^{-2} p_{x,y} S_{x,y} \]

\[ \frac{\sigma_{x,y}^{-2} p_{x,y} S_{x,y}}{\sum_y \sigma_{x,y}^{-2} p_{x,y}^2} \]

- two weighting factors:
  - \( p_{x,y} \) – profile value
    fractional flux
    normalised to unity
    \( \sum_y p_{x,y} = 1 \)
  - \( \frac{1}{\sigma_{x,y}^2} \) – (inverse) pixel noise
    read-out noise + photon noise
    \( \sigma_{x,y}^2 = \sigma_{rn}^2 + \sigma_{ph}^2 \)

- equivalent to scaling of (1D) spatial profiles \( p_{x,y} \)
- \( s_x \) (the intensity) is the best scaling factor
- \( s_x \) is unbiased (i.e. the extracted values are on average the true values; if the spatial profile is a good model)
- \( s_x \) has minimal variance
Optimal Extraction

• case photon-noise only:
  ▶ estimated photon-noise: \( \sigma_{x,y} = \sqrt{gS_{x,y}} \)  
    (gain \( g \): conversion factor between photon counts and digital counts)
  ▶ predicted pixel flux: \( S_{x,y} = p_{x,y}s_x \)
  ▶ estimated photon-noise: \( \sigma_{x,y}^2 = gp_{x,y}s_x \)

\[
s_x = \frac{\sum_y \sigma_{x,y}^{-2} p_{x,y} S_{x,y}}{\sum_y \sigma_{x,y}^{-2} p_{x,y}^2} = \frac{\sum_y S_{x,y}}{\sum_y p_{x,y}} = \sum_y S_{x,y}
\]

i.e. linear extraction

• same performance for high signal-to-noise
• better performance for low signal-to-noise
• in wings always low signal-to-noise
  extraction width not so important
Optimal Extraction

Comparison of Extraction Algorithms

Z Cha
Single Exposure

Optimal

Standard

Wavelength (Å)
Optimal Extraction

• How do we get the cross-section $p_{x,y}$?
  
  a. define an analytic function (e.g. Gaussian)
  b. from a reference object (e.g. flat field)
  c. from the observed object itself

• many algorithms

<table>
<thead>
<tr>
<th>Reference</th>
<th>Cross-section model</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hewett et al. (1985)</td>
<td>average along dispersion</td>
<td>assumes no order tilt</td>
</tr>
<tr>
<td>Horne (1986); Robertson (1986)</td>
<td>polynomials along dispersion</td>
<td>assumes small order tilt</td>
</tr>
<tr>
<td>Urry &amp; Reichert (1988)</td>
<td>Gaussian function</td>
<td></td>
</tr>
<tr>
<td>Marsh (1989)</td>
<td>coupled polynomials along dispersion</td>
<td>employs spatial subpixel grid</td>
</tr>
<tr>
<td>Piskunov &amp; Valenti (2002)</td>
<td>penalised splines</td>
<td>employs spatial subpixel grid</td>
</tr>
<tr>
<td>this work</td>
<td>(master flat)</td>
<td>requires stabilised spectrograph</td>
</tr>
</tbody>
</table>
Optimal Extraction

(Piskunov & Valenti, 2002)
Optimal Extraction
Optimal Extraction

- example profile modeling with REDUCE (Piskunov & Valenti, 2002) (penalised splines, chunk wise modelling)

low S/N (HET HRS spectrum)
Optimal Extraction

- example profile modeling with REDUCE (Piskunov & Valenti, 2002)

High S/N (HET HRS spectrum)
Extraction – cosmics

- cosmic ray hits
  - random events
  - number depends on exposure time
- outlier from the spatial profile
- kappa-sigma clipping to remove outlier
- requires noise model quantify the significance
- iterate profile modelling and extraction

Buchhave (2010), TRES spectrograph
Extraction – Cosmics

- cosmics in the raw images (HET HRS spectrograph)
Extraction – extracted spectrum

(HARPS, B star)
Wavelength calibration

- ThAr exposures
- emission line spectrum
- problem: saturated lines and blooming

Buchhave (2010), TRES spectrograph
Wavelength calibration

- extract ThAr spectra like the science images (and deblaze)
Wavelength calibration

- line identification on extracted spectra
- requires a line list atlas
Wavelength calibration

- wavelength solution: $\lambda_x = f(x)$

linear polynom (deg=1)  (IDL REDUCE)
Wavelength calibration

- wavelength solution: \( \lambda_x = f(x) \)

```
cubic polymom (deg=3) (IDL REDUCE)
```
Wavelength calibration

• not all lines are used
  ▶ unidentified lines
  ▶ blended lines
  ▶ Argon lines (for high precision RV, more age and pressure sensitive than Thorium)

• check line spread function (LSF)
Order merging

- extracted, wavelength calibrated spectrum

**TLS spectrum (Tautenburg)**

- order merging requires:
  - deblazing
  - rebinning to a common wavelength scale (sampling per resolution element is different)
  - error propagation and weighted coadding
Spectrum normalisation

- empirical normalisation (without standard star)

(IRAF, Subaru HDS)
**Flux calibration**

- derive instrument response with a spectrophotometric standard star
- extract standard star and compare with model spectrum

\[ \epsilon(\lambda) = \frac{I_{STD}^{XSH}(\lambda) \cdot 10^{0.4 \cdot Atm_{ext}(\lambda) \cdot (airp-aim) \cdot gain \cdot E_{phot}(\lambda)}}{T_{exp} \cdot A_{tel} \cdot I_{STD}^{ref}(\lambda)} \cdot factor \]

- extinction table
- airmass
- exposure time

- apply instrument response to object spectra
More complications

- truncated/gracing orders

\[ \text{wave map (Goldoni et al., 2006)} \]

- line tilt

\[ \text{spectral format X-Shooter (NIR)} \]
More complications

- sky emission lines

X-Shooter NIR (GJ 894.3, white dwarf, $V = 11.50$ mag)
More complications

- ghosts (parasitic orders)

(HARPS, flat)
References


Clayton, M. 1996, Introduction to Echelle Spectroscopy, ps


