The CRIRES Data Reduction Challenges

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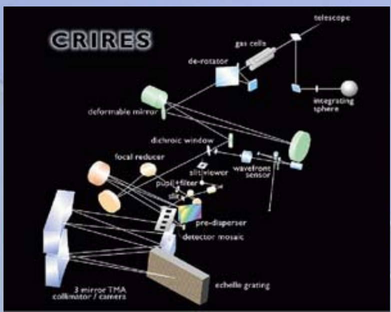
CRIRES Instrument Specificities

- CRIRES is CRyogenic high-resolution InfraRed Echelle Spectrograph
- CRIRES is located at the Nasmyth focus A of UT1 (Antu)
- CRIRES can boost all scientific applications aiming at fainter objects, higher spatial (extended sources), spectral and temporal resolution.
- Mosaic of four Aladdin III InSb arrays providing an effective 4096 x 512 focal plane detector array
- Adaptive Optics with MACAO



Wavelength range	0.95 – 5.2 microns
Resolving Power	100,000
Slit width	0.2 – 1 arcsec
Slit length	40 arcsec
Pixel size (spatial dir.)	0.086 arcsec
Adaptive optics feed	60 actuators curvature sensing system
Calibration system	Integrating sphere / line lamps
Slit viewer	Aladdin array, J, H, K and 2 neutral density H filters, 0.045 arcsec/pixel
Pre-disperser	ZnSe prism
Echelle grating	40x20 cm, 31.6 lines/mm, 63.5 deg. blaze
Detector array	4096x512 pixels using 4 Aladdin arrays, with inter-detector gaps of 283 pixels

CRIRES Data

Primary header	•Usual FITS mandatory keywords •WCS keywords •Observation related keywords •Template related keywords •**Data Classification keywords** •Various information about the carriage, the field selector, the filters, the de-rotator, the lamps, etc…
Primary data unit	EMPTY
Extension 1 header	•Usual FITS mandatory keywords HIERARCH ESO DET CHIP NO = 1 HIERARCH ESO DET CHIP NX = 1024 HIERARCH ESO DET CHIP NY = 1024 HIERARCH ESO DET CHIP X = 1 HIERARCH ESO DET CHIP Y = 1 HIERARCH ESO DET WIN NX = 512 HIERARCH ESO DET WIN NY = 1024
Extension 1 data unit	
Extension 2 header	HIERARCH ESO DET CHIP NO = 2 HIERARCH ESO DET CHIP X = 2
Extension 2 data unit	
Extension 3 header	HIERARCH ESO DET CHIP NO = 3 HIERARCH ESO DET CHIP X = 3
Extension 3 data unit	
Extension 4 header	HIERARCH ESO DET CHIP NO = 4 HIERARCH ESO DET CHIP X = 4
Extension 4 data unit	

Basic description:
- FITS compliant
- DICB compliant
- 4 extensions files (1 / detector)
- 32 bits single precision floating point
- 8.4 Mb each for 4*512*1024 pixels
- About 1 or 2 Gb per night

The data are automatically classified with the Data Classification keywords (DPR.CATG, DPR.TECH, DPR.TYPE).

These keywords uniquely define the kind of CRIRES file they are written into (Science observation, calibration lamp for wavelength calibration, flat field observation, standard star obtained with nodding, etc…).

The system automatically decides using those keywords which pipeline recipe it will execute in order to reduce the data.

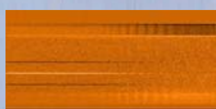
Example:
HIERARCH ESO DPR CATG = 'CALIB'
HIERARCH ESO DPR TECH = 'SPECTRUM'
HIERARCH ESO DPR TYPE = 'FLAT'

Define a CRIRES flat-field calibration file that needs to be reduced by the system with the crires_spec_flat recipe. The association between the DPR keywords and the recipes is defined in the pipeline package.

Data Reduction Pipeline Recipes

Calibration Recipes:
- **crires_spec_dark: Produces the dark calibration file**
- **crires_spec_flat: Produces the flat-field and the bad pixels map**
- **crires_spec_detectrans: Compute photometric transfer function for each detector**
- **crires_spec_wavecal: Compute the wavelength calibration with gas cells, lamps, or sky emission frames**

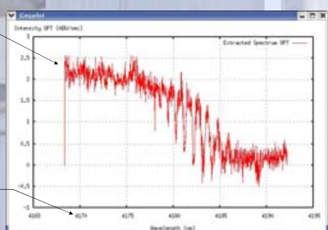
Observation Recipe:
- **crires_spec_jitter: This recipe is able to reduce the different kind of observations offered with CRIRES. It can handle jittering, nodding, or standard stars observations. It accepts calibration files as dark, flat, bad pixels maps, as well as wavelength calibration solutions. Every detector is reduced separately.**
  It performs successively:
  - **Images combination (crires_util_combine)**



- **Spectrum extraction (crires_util_extract)**
- **Wavelength calibration**
  (crires_util_extract + crires_util_wavecal)
  If a wavelength calibration solution is provided, this one will be used. Otherwise, the sky lines are used

Wl(pix) = 4168.31
+ 0.0233392 * pix
– 4.48189e-8 * pix * pix

- **Wavelength computation (crires_util_wlassign)**
- **Conversion factor computation (crires_util_conversion)**
- **Sensitivity computation (crires_util_sensitivity)**

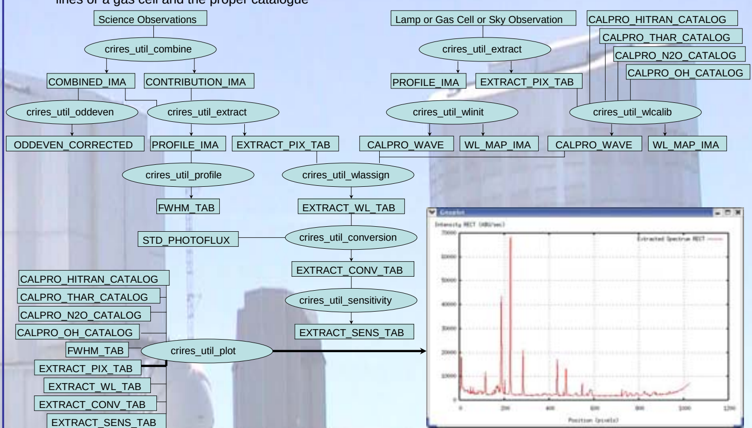


Data Reduction Pipeline Utilities

The different utilities allow a flexible data reduction, and a better control of the intermediate products

Main utilities:
- **crires_util_combine:**
  Science observations images combination (nodding and jitter are handled)
- **crires_util_extract:**
  Optimal and Rectangular spectrum extractions
- **crires_util_wlcalib:**
  Wavelength Calibration using a lamp, emission lines or a gas cell and the proper catalogue

Main intermediate products:
- **COMBINED_IMA:** The combined image
- **CALPRO_WAVE:** The wavelength calibration solution
- **EXTRACT_WL_TAB:** The extracted spectrum (in wavelength)
- **EXTRACT_SENS_TAB:** The extracted spectrum (in wavelength), the sensitivity, the conversion factor, the throughput. Only for standard stars.

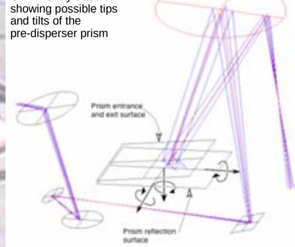


Physical Model

Automatic wavelength calibration is a difficult problem for any state of the art spectrograph. For CRIRES the situation is complicated by the following specific issues:
- **High resolution: known calibration source spectral features are well spread out such that at most a few (and sometimes none) are found on a given detector chip.**
- **High sensitivity: CRIRES detects lines not present in existing line lists for standard calibration sources.**
- **Discontinuous detector array: gaps between the chips confuse the spectral feature matching process.**

These issues make the automatic elimination of false matches and obtaining a well defined fit for some CRIRES wavelength settings almost impossible using an empirical approach.

As an alternative we have developed a physical model based approach to CRIRES wavelength calibration:
- **A simplified ray trace model describes the CRIRES dispersive optics.**
- **Spectral features are identified in a series of wavelength calibration exposures.**
- **The model parameters (tips and tilts of the critical components) are optimized so that the model reproduces the measured spectral feature locations (in 2D).**
- **Science exposures are calibrated by setting the model prism and grating angles (which define the wavelength range) to match the header values and using the calibrated model to compute the 2D dispersion relation.**
- **Possible to optimize the prism and grating values using contemporaneous calibration exposures (removing the reliance upon header values).**



Section of simplified CRIRES ray trace showing possible tips and tilts of the pre-disperser prism

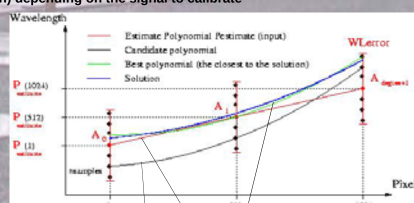
Advantages:
- **Combines data from many calibration exposures to produce a solution that is valid for the entire wavelength range.**
- **Provides a 2D solution for the detector array**
- **The model parameters have a physical basis, providing insight into the status of the instrument.**

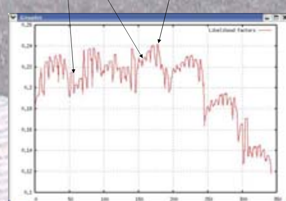
The modeling approach will be discussed in greater detail by Paul Bristow during the "Data Flow and Data Reduction Software" session.

Wavelength Calibration

Inputs:
- **The Estimate Polynomial (coming from the physical model or a previous computation in an iterative process)**
- **The Wavelength Error of the estimate (WLerror)**
- **The degree of the searched polynomial (degree)**
- **The number of samples (nsamples)**
- **The lines catalogue (OH, Gas cell, Lamps, Hitran) depending on the signal to calibrate**
- **The signal to calibrate (in pixels)**

Algorithm:
1. **Consider degree+1 positions Ai regularly spaced, and nsamples points spread within WLerror around these positions**
2. **For each possible sequence of points (nsamples^(degree+1) possibilities), the interpolation polynomial is created and considered as candidate**
3. **The candidate polynomial is used to convert the signal to calibrate from pixels to wavelengths. This signal is compared to the signal generated from the catalogue. A likelihood coefficient is computed**
4. **The best likelihood parameter gives the best candidate, i.e. the polynomial that is the closest to the solution**
5. **A second pass (or more) is used to refine the solution with the first pass solution used as estimate, with a smaller WLerror and a higher degree.**





Advantages:
- **The method is very generic. It is used for CRIRES and SOFI. It will be used for ISAAC, NACO and VISIR.**
- **The best likelihood factor gives a good idea of the quality of the final calibration**
- **There is no line detection involved, it works also for noisy signals (interesting in infrared)**