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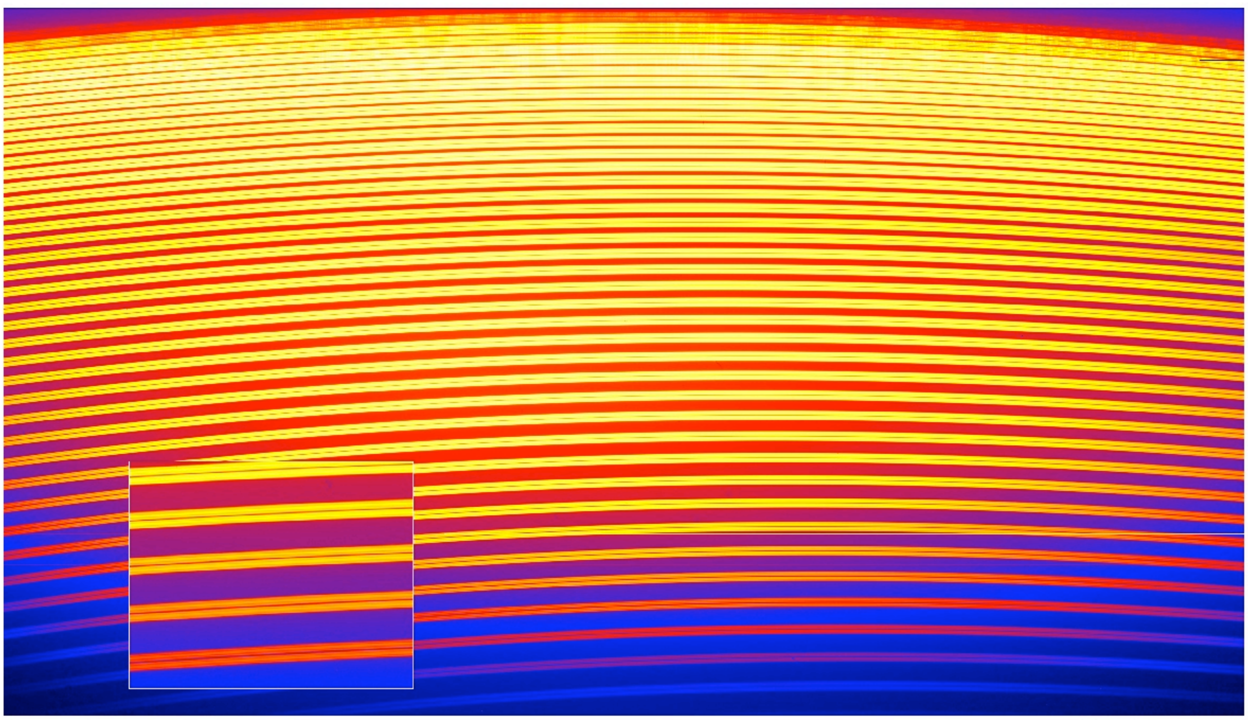
OPERA PIPELINE PROJECT

A Welcome To PIs



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1. Introduction

Welcome to the OPERA pipeline! The OPERA team is delighted be able to share with you a brief overview of what you can expect to find in distributions of OPERA-reduced programs . As you know, OPERA-1.0 is the Open Source pipeline developed at CFHT to replace Upena and J.F.Donati's Libre Esprit software (Donati et al. 1997[1]). OPERA offers unparalleled transparency of calibration and reduction data as well as extensive product and byproduct visualizations of calibration and reduction.

This brief "welcome" is intended to quickly introduce you to the new products and byproducts of the pipeline. Please see the opera-Final Design document to pursue more detailed explanations of these products.

We have made every effort to also produce backward-compatible products to Upena and Libre-Esprit. That said, in addition we offer much more access to the various calibrations and data outputs along the way.

One obvious change that is pervasive is the use of compression to reduce file size and improve download speeds. Text files are gzipped and FITS files are RICE compressed.

OPERA is a complete rewrite of an echelle spectro-polarimeter reduction pipeline. The methods used and the calibrations, such as the aperture, the instrument profile, etc., are different than that used by Libre-Esprit. As such the results, while similar do not match that of Libre-Esprit directly.

In section 2 of this document we discuss the calibration products. Section 3 is devoted to reduction products. Section 4 discusses Libre-Esprit-compatibility products and section 5 concludes this document.

2. OPERA Calibrations

All of the calibration products below are in plain-text gzipped format. The text files are self-identifying, giving the type of calibration and the file contents in the preface. In all cases there is one calibration per detector, amplifier configuration, mode, speed set.

2.1 Bias / Gain (.bias.gz)

The gain/bias calibration stores gain, noise and median bias level of each amplifier. It is used in extraction, in particular, to support 2-amp mode. The product contains the number of amplifiers and the gain and noise as well as the detsec for each amplifier.

2.2 Order Spacing Polynomial (.ordp.gz)

The order spacing polynomial is a polynomial fit to the measured spacing between spectral orders as a function of the order center position on the detector along the spatial direction (across dispersion).

2.3 Geometry (.geom.gz)

The geometry product contains order center points obtained from a master flat-field image. An optimal polynomial is fit to produce a model of the data. The output gives the order of the polynomial for each order, the polynomial coefficients and coefficient errors.

2.4 Instrument Profile (.prof.gz)

The instrument profile is a two-dimensional oversampled normalized profile truncated at a given size. Typically for ESPaDOnS we set a 30 pixel (column) x 5 pixels(row) window, which is oversampled by a factor of 5 in each direction. The result is stacked into a normalized two-dimensional oversampled profile for a given minimum bin-size and minimum number of spectral lines. A polynomial is fit in the dispersion direction for each oversampled sub-pixel. This gives a model for the two-dimensional IP at any position within the order, or at any dispersion element. Note that since the IP gives a more accurate measurement of the illumination profile, it allows a better estimate of the order center and therefore a refinement of the geometry model.

2.5 Extraction Aperture (.aper.gz)

The extraction aperture uses the two-dimensional IP to measure the orientation of a given slit. The slit shape is assumed to be rectangular, allowing the user to select a number of beams within which the slit divided into independent flux measurements. Each aperture beam is an oversampled, tilted rectangle with fixed dimensions. The tilt is measured as the angle that maximizes the flux fraction per spectral element. Two additional smaller apertures are created on both sidess of the slit for background estimates.

2.6 Wavelength (.wcal.gz)

The wavelength polynomials are created from the two-dimensional instrument profile and geometry to detect spectral lines in a comparison lamp exposure, by means of cross-correlation. ESPaDOnS uses a Th-Ar atlas as comparison. Calibration starts from an initial hint (wavelength at the center of each order) to select a set of known spectral lines from the reference atlas. OPERA currently uses the atlas of Lovis & Pepe (2007). The spectral lines in the atlas are matched against those measured from the comparison image. The match is performed by searching the highest correlation between the line positions in the image and in the atlas. The module uses the operaWavelength class to store a vector of wavelengths (nm) and distances (in pixel units) for a set of spectral lines identified from the master comparison image. An optimal polynomial is fit to model the data and create the calibration file consisting of the polynomial coefficients and coefficient errors.

2.7 Dispersion Polynomial (.disp.gz)

The dispersion polynomial is a calibration product given by a series of Laurent polynomials. Each of these polynomials consists of a fit to one coefficient of the pixel-to-wavelength solution obtained for all orders. This calibration provides a dispersion model for the pixel-to-wavelength solution as a function of the echelle spectral orders.

2.8 Flux Calibration (.fcal)

Flux calibration is done in two steps. First standard stars taken under photometric conditions are reduced to produce a calibration for each standard star. The output calibration file contains the spectral dependency of the conversion factor between the measured flux and the flux in the same units as the input template per unit of time (s). Secondly master flux calibrations are created for each mode/speed of the instrument. The input calibration files don't necessarily need to contain the same sampling or same number of points. The output file will be resampled (by spline interpolation) to the same grid as in the input reference spectrum. This module runs every night to combine all calibrations available and create a master calibration file for that night, where many observations of standard stars may be available. However the same module can also be used to produce a master calibration file for an entire run or for all the lifetime of the instrument. The method to combine data points from multiple calibrations can be selected, however the only method available currently is the average.

2.9 Master Bias (masterbias_....fits.fz)

The master bias for each detector, amplifier configuration, mode and speed is a median combined image of like calibration images with lower noise and free of cosmic rays.

2.10 Master Comparison (mastercomparison_....fits.fz)

The master comparison for each detector, amplifier configuration, mode and speed is a median combined image of like calibration images.

2.11 Master Fabry-Perot (masterfabperot_....fits.fz)

The master Fabry-Perot for each detector, amplifier configuration, mode and speed is a usually the single image taken during calibration.

2.12 Master Flat (masterflat_....fits.fz)

The master flat for each detector, amplifier configuration, mode and speed is a median combined image of like calibration images with lower noise and free of cosmic rays.

3. OPERA Reduction Products

All of the reduction products below with a .gz extension are in plain-text gzipped format. The text files are self-identifying, giving the type of calibration and the file contents in the preface. All of the reduction products below with a .fz extension are RICE compressed floating point binary image FITS format images.

These products are grouped together since there is one product produced per image, though the barycentric and radial velocity products might also be considered as calibrations..

3.1 Beam Spectra (.e.gz)

The extraction module makes use of all calibrations to optimally extract the energy flux information for each wavelength element from an input two-dimensional echellogram spectral image. The bias subtraction, flat-field corrections, and bad-pixel masks are used in extraction. The product contains multiple vectors of flux, variances, backgrounds and wavelength values, obtained for each individual beam, using Optimal Extraction.

3.2 Polarimetry (.p.gz)

The spectro-polarimetric OPERA product, consists of the measurements of the degree of polarization for a given Stokes parameter. For spectro-polarimetry, ESPaDOnS is operated in polar mode, which requires a minimum of four exposures in order to create a single polarimetric product for each Stokes parameter (Q, U or V). Each of these exposures is obtained with the retarding plates in specific rotations with interleaving positions, which allow a differential measurement of the degree of polarization.

This module uses the flux information obtained from extraction. Therefore it also provides the usual intensity spectrum (Stokes I) for each individual exposure.

3.3 Telluric Correction (.tell.gz)

This calibration for each image identifies atmospheric emission/absorption spectral lines on science images to improve the wavelength calibration. The signal-to-noise for these lines depends on the exposure time and on the target brightness, therefore the quality of this correction is not consistent for all objects observed. For this reason, this module produces an additional vector of corrected wavelength values.

3.4 Barycentric Radial Velocity Correction (.rvel.gz)

The barycentric radial velocity for each observation, calculated based on the time and direction of the target.

3.5 Spectrum/Calibrations Container (m.fits)

The products of a calibration and reduction are stored in Multi-Extension (MEF) FITS format for archival storage. It is important that enough information be stored in the FITS file so that many years later, the reduction and calibration can be reproduced. The OPERA pipeline produces much more information about the calibrations and reduction than did

Libre-Esprit. It was thought better to take advantage of the switch to OPERA to add a Product format to store the additional information, provided that we also include a tool in OPERA that can extract the spactrum, calibration files, and original Libre-Esprit format text files for compatibility.

The various calibrations are most easily stored as floating point image data. But, how to handle the varying widths and depths of the data?

The most natural solution is to use multi-extension FITS format.

Each of the calibrations noted above are stored as separate extensions (except the master images). One may view the m.fits product using a viewer such as saoimage ds9. The headers contain a description of the format of the binary data, The extended format beam spectrum is also stored (e.gz), as all of the backward compatibility and normalized, telluric, barycentric products may be derived from that beam spectrum and the calibrations in the product. This there is no need to store the iu,s, in,s, iuw,s, in,s data.

Note that some products will have more extensions, depending on available calibration data, and also the first image in a sequence of polarimetric exposures contains the polarimetry data.

A tool called operaExtractProducts is available to extract all of the extensions into there original containers.

4. Libre-Esprit Compatibility Products

4.1 Spectra (.s.gz)

OPERA produces (in LE_compatibility mode) .the familiar iu.s, in.s, in.s, inw.s, ps., pu.s, pn.s, puw.s, pnw.s, and .sn text files (in gzipped format).

4.2 Polarimetry Container (p.fits.fz)

This container is a FITS floating point binary image. For each Polar sequence, with the first odometer in the sequences, the p.fits.fz contents are:

1.Contents of the pu.s file. 2.Contents of the pn.s file. 3. Contents of the puw,s file. 4. Contents of the pnw.s file 5. Central SNR values for each order.

Additionally the calculated gain and bias is added as keywords to the primary header. The output of the Libre-Esprit .out and .dat files which are currently stored as comments, are not be available..

4.3 Intensity Container (i.fits.fz)

This container is a FITS floating point binary image. It contains the iu.s file (wavelength, un-normalized), the in.s file (wavelength, normalized), the iuw.s file (wavelength, autowave, un-normalized), the inw.s file (wavelength, autowave, normalized) spectra, and central SNR values for each order.

5. Conclusion

OPERA's transparency affords a richness of data not before available. This document described the calibration and reduction products and the containers that retain this information in archival format for posterity .

Appendix A - References

[1] Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E., and Cameron, A. C., "Spectropolarimetric observations of active stars," MNRAS 291, 658–682 (1997).