

Supplementary wavelength calibration methods for SALT/RSS spectropolarimetric observations

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Abstract

TODO:

- Done last
- Flow from use of SALT and pipeline and basics of its science implementations into why a more streamlined wavelength calibration is an improvement.
- Give summary of results.
- Aim for a paragraph (~ 600) without going too in-depth into anything specific.
- Brian's comment: Abstract should summarize paper. Include results, conclusions, etc.

Keywords:

TODO:

- Add Keywords → look up the astronomy journal keywords
- Look up keywords for pipeline development and data reduction.
- I.E. Polarization: optical, Calibration: wavelength, galaxies: AGN, Blazars, Pipeline, SALT, etc.

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I hereby acknowledge and express my sincere gratitude to the following parties for their valuable contributions:

- **TODO: Add acknowledgements!**

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Chapter 1

Introduction

TODO: Very short intro to Spectroscopy, Polarization, and Spectropolarimetry and their importance in astronomy

TODO: Problem Statement, VERY IMPORTANT, roughly a sentence but problem thoroughly fleshed out.

TODO: Focus on AGN implications and implementations such as the types of objects and a short history for each type of object, Blazar focus with specification on BL Lacs and FSRQs, the Unified Model, ~~The Blazar sequence~~

TODO: Brian's comment: Highlight importance of polarimetry for understanding emission and how that plays a role in AGN.

TODO: Basics of modelling (Different energy/wavelength ranges used and what the models tell us about emission processes/structure) so that Hester's results can be noted for applications of the pipeline.

TODO: General layout of Dissertation

Chapter 2

Spectropolarimetry and the SALT RSS

This chapter gives an overview of the basics of spectropolarimetry (§ 2.3), and how it functions, following from the principles of both spectroscopy (§ 2.1) and polarimetry (§ 2.2). Further, it is discussed how these techniques are practically implemented for Southern African Large Telescope (SALT) (§ 2.4), using the Robert Stobie Spectrograph (RSS) (§ 2.4.3), and how the spectropolarimetric reduction process is completed (§ 2.4.3).

2.1 Spectroscopy

Spectroscopy originated in its most basic form with Newton's examinations of sunlight through a prism (Newton and Innys, 1730) but came to prominence as a field of scientific study with Wollaston's improvements to the optics elements (Wollaston, 1802), Fraunhofer's use of a diffraction grating instead of a prism (der Wissenschaften, 1824), and Bunsen and Kirchoff's classifications of spectral features to their respective chemical elements (Kirchhoff and Bunsen, 1861).

The simplest spectrometer schematic, as shown in Figure 2.1, consists of incident light collected from the telescope's optics, labelled A, being focused onto a slit, B, and passed through a collimator, C. The collimator collimates the light allowing a dispersion element, D, to disperse the light into its constituent wavelengths. The resultant spectrum is focused by camera optics, E, onto a focal plane, F. Viewing optics are situated at the focal plane in the case of a spectroscope and a detector is situated at the focal plane in the case of a spectrograph.

2.1.1 Telescope Optics

The telescope optics refers simply to all the components of a telescope necessary to acquire a focal point at the spectrometer entrance, labelled B. The focal point in most traditional telescope designs is fixed relative to the telescope and so the spectrometer may be mounted at that point. In cases where the telescope is designed to have a moving focal point relative to the telescope (see Buckley et al., 2006; Cohen, 2009; Ramsey et al., 1998), the spectrometer, or a signal transfer method such as a fibre feed to the spectrometer, must also move along the telescope's focal path.

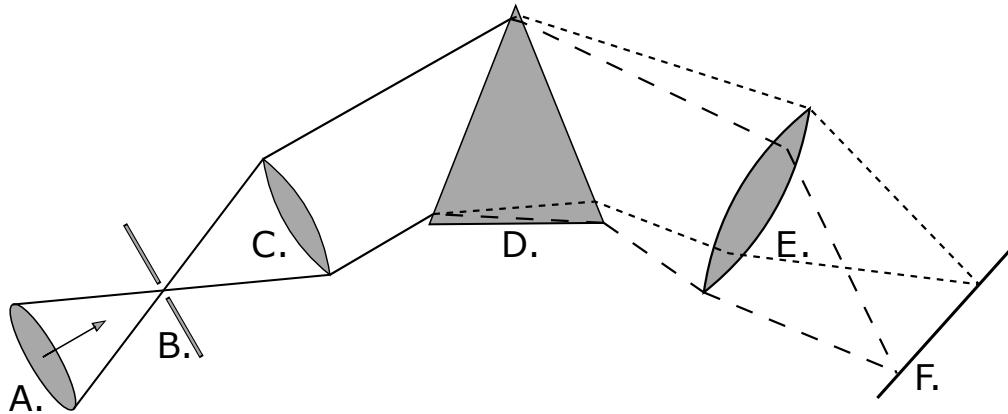


Figure 2.1: Layout depicting the light path through a spectrometer. Diagram adapted from Birney et al. (2006).

2.1.2 Slit

The slit's function is to control the amount of incident light entering a spectrometer and, along with the exposure time of the detector, prevents over-exposures of bright sources on highly sensitive detectors (Tonkin, 2013). If a source is spatially resolvable, or larger than the seeing conditions, the slit additionally acts to spatially limit the source to increase the spectral resolution, resulting in sharper features in the resultant spectrum. Without the slit the spectral resolution would be determined by the projected width of the source on the detector, or the seeing if the source was a star-like point source. Increasing the spectral resolution comes with the trade-off of decreasing the light collected from the source and thus acquiring a less intense resultant spectrum. Multiple spectra may be acquired simultaneously when the slit is positioned such that collinear sources lie along the slit.

The spectrometer is usually situated at the focal point. In cases where this is not feasible due to restrictions, for example restrictions of weight or size, a fibre feed may be situated behind the slit on the telescope. This allows the signal to be routed away from the telescope to a controlled environment with only minuscule losses.

2.1.3 Collimator

The collimators function is to collimate the focused light from the telescope, ensuring that all light rays run parallel before reaching the dispersion element. The focal ratio of the collimator (f_c/D_c , where f refers to the focal length and D refers to the diameter) should ideally match the focal ratio of the telescope (f_T/D_T).

2.1.4 Dispersion Element

Including a dispersion element in the optical path is what defines a spectrometer. As the name suggests, a dispersion element disperses the light incident on it into its constituent wavelengths and produces a spectrum. There are two types of dispersion elements, namely the prism and the diffraction grating, which operate on different principles, as discussed in § 2.1.7.

2.1.5 Camera Optics

The lens functions similarly to that of the telescope's optics but in this case focuses the dispersed light onto a receiver situated at the focal plane. As mentioned previously, an eye piece is fixed to the focal point for a spectroscope while a spectrograph employs a detector.

2.1.6 Detector

The two most prevalent detector types in spectroscopy are the Charged-Coupled Device (CCD) and Complementary Metal-Oxide-Semiconductor (CMOS) detectors. In astronomical spectroscopy however, sources are fainter and exposure times are much longer and so the CCD detectors are by far the preferred detector as their output has a higher-quality and lower-noise when compared to CMOS cameras under the same conditions (Janesick et al., 2006).

The CCD is a detector composed of many thousands of pixels which can store a charge so long as a voltage is maintained across the pixels. Each pixel detects incoming photons using photo-sensitive capacitors through the photoelectric effect and converts the photons to a charge (Buil, 1991). There are also thermal agitation effects which introduce noise to the charge accumulated by a pixel, further discussed in § 2.1.8. Once the exposure is finished the accumulated charge is read column by column, row by row, through an Analog-to-Digital Converter (ADC) which produces a two-dimensional array of ‘counts’.

2.1.7 Dispersion of Light

Light can be broken up into its constituent wavelengths through two different physical phenomena, namely dispersion and diffraction, which dispersive elements use to create spectra. Dispersive prisms and diffractive gratings each have their strengths and weaknesses and a wide spectrum of instruments exist which implement either, or both, concepts. Regardless of the specific element, dispersive elements all have a resolving power, R , and an angular dispersion. Generally, while the angular dispersion is a more involved process to determine, the resolving power of a spectrograph can be measured as:

$$R = \frac{\lambda}{FWHM}, \quad (2.1)$$

where λ is the wavelength of an incident monochromatic beam and Full Width at Half Maximum (FWHM) refers to the width of the feature on the detector at half of its maximum intensity.

Prism

The prism operates on the principle that the refractive index of light, n , varies as a function of its wavelength, λ . Prisms were the only dispersive elements available for early spectroscopic studies, but they were not without flaw. The angular dispersion of a prism is given by:

$$\frac{\partial\theta}{\partial\lambda} = \frac{B}{a} \frac{dn}{d\lambda}, \quad (2.2)$$

where θ is the angle at which the refracted light differs from the incident light, λ is the wavelength of the incident light, B is the longest distance the beam would travel through

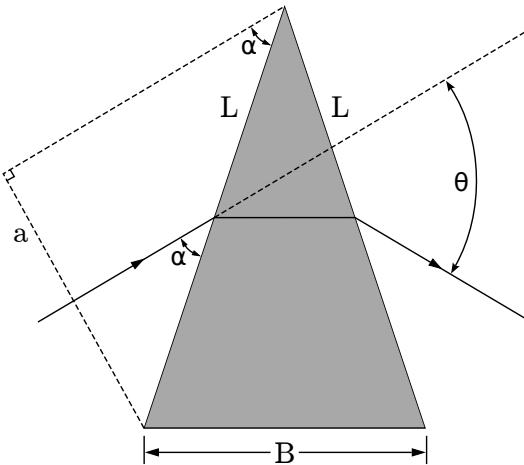


Figure 2.2: Geometry of a prism refracting an incident monochromatic beam at a minimum deviation angle. Diagram adapted from Birney et al. (2006).

the prism. $a = L \sin(\alpha)$ is the maximal beam width that would fit onto a prism with a transmissive surface of length L for a given angle, α , at which a beam would strike the transmissive surface, as shown in Figure 2.2.

The refractive index of a material as a function of its wavelength, $n(\lambda)$, can be approximated by Cauchy's equation:

$$n(\lambda) = A_C + \frac{B_C}{\lambda^2} + \frac{C_C}{\lambda^4} + \dots, \quad (2.3)$$

where A_C, B_C, C_C are the Cauchy coefficients and have known values for certain materials. Cauchy's equation is a much simpler approximation of the refractive index that remains very accurate at visible wavelengths (Jenkins and White, 1976). Taking only the first term of the derivative of the Cauchy equation allows us to approximate the angular dispersion of a prism,

$$\frac{\partial \theta}{\partial \lambda} = -\frac{B}{a} \frac{2B_C}{\lambda^3} \propto -\lambda^{-3}, \quad (2.4)$$

which shows that the angular dispersion of a prism is wavelength dependent and furthermore that longer wavelengths are dispersed less than shorter wavelengths (Birney et al., 2006; Hecht, 2017). The dependence of the angular dispersion, $d\theta/d\lambda$, on the wavelength, λ , is crucial for the formation of a spectrum but this cubic, non-linear, relation results in a non-linear spectrum. Since prisms rely on the refractive index of the material they are made of, they have low angular dispersions.

Multiple prisms can be used to increase the angular dispersion but as the dispersion is non-linear it becomes increasingly more difficult to calibrate. The more material and material boundaries the light must pass through, the more its intensity decreases due to attenuation effects and Fresnel losses. Even so, the transmittance of modern prisms for their selected wavelength range is generally very high due to improved manufacturing methods as well as improved transmitting materials.¹

¹See manufacturers technical specifications, THORLABS, or Edmund Optics for example.

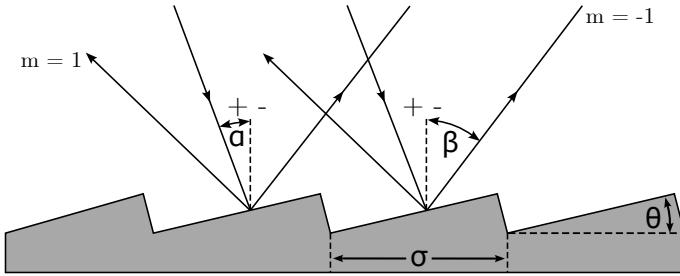


Figure 2.3: Geometry of a reflective blazed grating refracting an incident monochromatic beam. Diagram adapted from Birney et al. (2006).

Diffraction grating

The alternative dispersing element is a diffraction grating, which operates on the principle that as light interacts with a grating where the groove size is comparable to the light's wavelength, the light is dispersed through constructive and destructive interference. This interference results in multiple diffracted beams m , called orders, either side of a central reflected, or transmitted, beam such that $m \in \mathbb{Z}$, where $m = 0$ is the non-dispersed, or reflected, beam.

An example of a reflective blazed grating is illustrated in Figure 2.3. Here a monochromatic beam is incident on the grating at an angle of α from the grating normal. Due to the interference, a diffracted beam of wavelength λ is found at an angle of β from the grating normal. The relation between the incident and diffracted beams is given by the grating equation:

$$m\lambda = \sigma(\sin(\alpha) \pm \sin(\beta)), \quad (2.5)$$

where σ is the groove spacing of the grating and m is the order of the diffracted beam being considered. The grating equation also applies to transmission gratings, though care should be taken for the signs of α and β .

Equation 2.5 also shows that different diffracted beams may share an angle of dispersion for beams not in the same order. The regions of an order that do not overlap with another order are called free spectral ranges. An order-blocking filter may be used to account for the overlaps and increase the free spectral range. A diffraction grating can also be blazed by an angle θ , as illustrated in Figure 2.3. Blazing refers to the fact that the grooves on the surface of the grating are not symmetrical. The asymmetry of the grooves diffracts the incident beam such that most of the beam's intensity is found in a reflected, zeroth order, beam. The wavelength at which a blazed spectrograph is most effective is called the blaze wavelength, λ_b , which is determined by:

$$\begin{aligned} m\lambda_b &= 2\sigma \sin(\theta) \cos(\alpha - \theta), \text{ where} \\ 2\theta &= \alpha + \beta. \end{aligned} \quad (2.6)$$

Taking the derivative of Equation 2.5 with respect to λ while keeping α constant, allows us to determine the angular dispersion of a diffraction grating,

$$\frac{\partial \beta}{\partial \lambda} = \frac{m}{\sigma \cos(\beta)}. \quad (2.7)$$

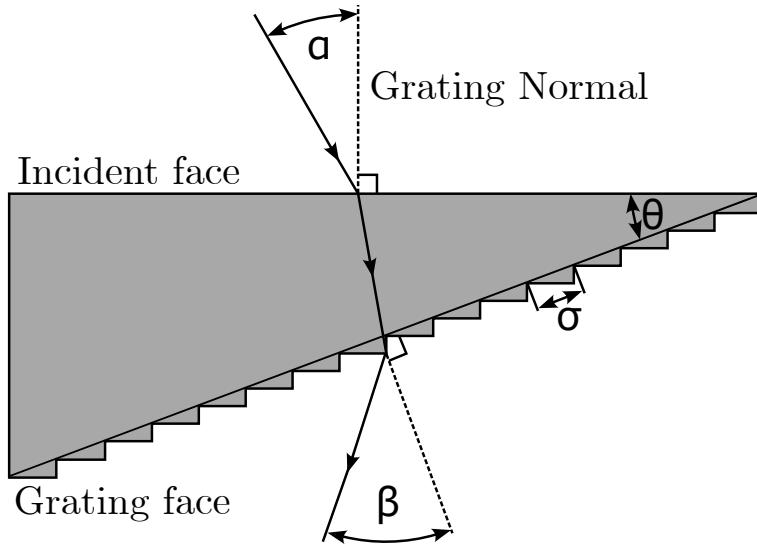


Figure 2.4: Diagram of a grism for an incident monochromatic beam of light and a diffracted beam of order $m = 1$. Diagram adapted from Birney et al. (2006).

Substituting m/σ with the grating equation results in

$$\frac{\partial\beta}{\partial\lambda} = \frac{\sin(\alpha) + \sin(\beta)}{\lambda \cos(\beta)} \propto \lambda^{-1}. \quad (2.8)$$

Similar to the dispersion of a prism, Equation 2.8 shows that the dispersion of a grating is wavelength dependent, but this dependence is only inversely proportional and thus more uniform across a wavelength range than that of a prism. Furthermore, shorter wavelengths are refracted less than longer wavelengths since there is no negative relation between the angular dispersion and the wavelength (Birney et al., 2006; Hecht, 2017).

Alternate Diffraction Elements

As mentioned before, multiple subgroups exist for both dispersive prisms and diffractive gratings. For prisms, along with the single and multiple prism setups mentioned, there also exists grisms and immersed gratings. A grism (Grating Prism), as shown in Figure 2.4, refers to a transmissive grating etched onto one of the transmissive faces of a prism and allows a single camera to capture both spectroscopic and photometric images without needing to be moved, with and without the grism in the path of the beam of light, respectively. An immersed grating refers to a grism modified such that the transmissive grating is coated with reflective material. The primary source of dispersion for both grisms and immersive gratings is the grating and any aberration effects from the prism are negligible in comparison.

Other types of gratings include the Volume Phase Holographic (VPH) grating as well as the echelle grating. The VPH grating consists of a photoresist, which is a light-sensitive material, sandwiched between two glass substrates. Diffraction is possible since the photoresist's refractive index varies near-sinusoidally perpendicularly to the gratings lines, as seen in Figure 2.5. This allows for sharper diffraction orders and low stray light scattering as compared to more traditional gratings but since blazing is not possible the

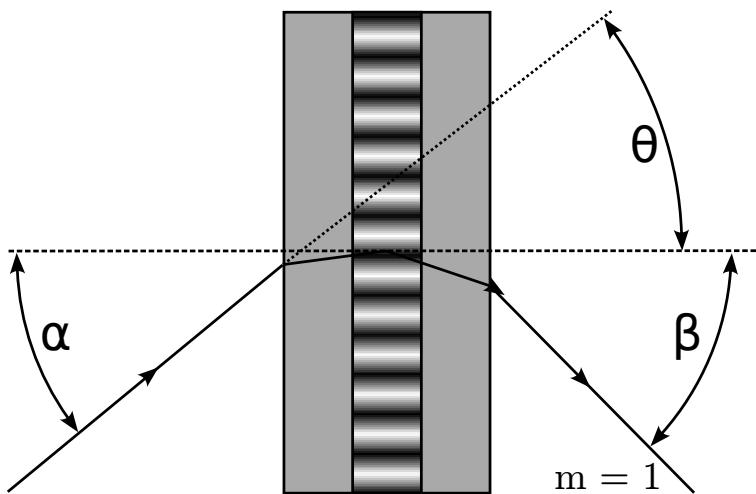


Figure 2.5: Diagram of a VPH grating for an incident monochromatic beam of light. Diagram adapted from Birney et al. (2006).

efficiency is decreased. An echelle grating refers to a diffraction grating with higher groove spacing which is optimized for use at high orders. The high order of the diffracted beam allows for greater angular dispersion which is most useful when combined with another dispersion element to cross-disperse a spectrum, resulting in a high resolution spectrum.

2.1.8 Detector and Spectroscopic Calibrations

Acquiring a spectrum from observations is more involved than simply reading out the data recorded on the CCD. A raw science image, which is the raw counts of the observed source read from the CCD with no calibrations applied, has on it a combination of useful science data as well as noise. The noise is a combination of random noise introduced through statistical processes and systematic noise introduced through the instrumentation and the observation conditions the source was observed under. This noise causes an uncertainty in the useful data and can be minimized, predominantly by calibrating for the systematic noise, but never fully removed (Howell, 2006).

The dominant source of noise in a raw image is detector noise. CCDs are manufactured to have a small base charge in each pixel, called the ‘bias’ current which allows the readout noise, a type of random noise, to better be sampled. There is also an unintentional additional charge which is linearly proportional to the exposure time and originates from thermal agitation of the CCD material, called the ‘dark’ current. The dark current can be minimized and possibly ignored if the CCD is adequately cooled. These types of noise add to the charge held by a pixel and are thus considered additive.

The CCD is not a perfect detector and the efficiency of it and the optics of the telescope also contribute noise to the image. The efficiency of a CCD is referred to as the Quantum Efficiency, and it is a measure of what percentage of light striking the detector is actually recorded and converted to a charge. The efficiency of the CCD and telescope optics is also wavelength dependent and so the noise that results from them is more complex than that of additive noise. This type of noise is referred to as multiplicative noise.

Additive noise, such as bias and dark currents, is inherent to CCD images, and as such

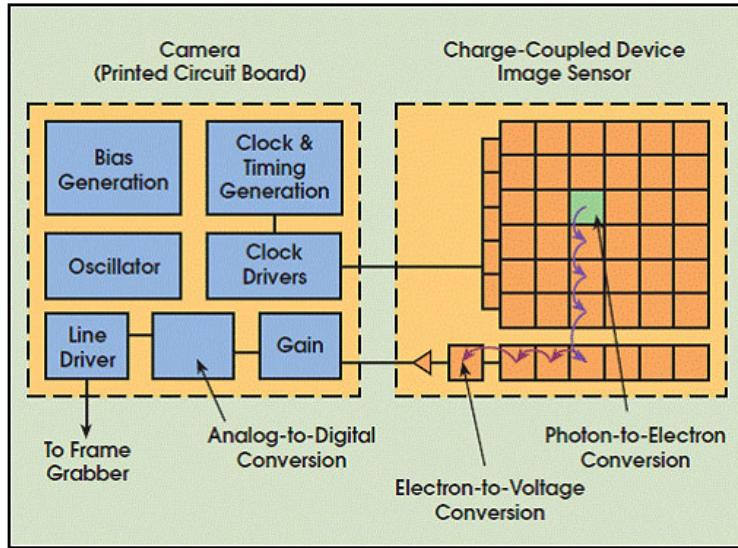


Figure 2.6: Diagram of the inner logic of a CCD. Figure adapted from Litwiller (2001).

needs to be subtracted out first when performing calibrations. Bias currents can be found by taking a bias image or by adding an overscan region to each image. A bias image is an image where the charges on the CCD are reset and then immediately read off without exposing anything on the detector, effectively taking an image with zero exposure time. Alternatively, to save time during an observational run, overscan regions may be added to the images. An overscan region refers to adding a few cycles to the readout of each column of the CCD such that the base current is read out and appended to each image.

Dark currents can be found by taking an image with nothing exposed onto the detector for a certain exposure time. This resultant dark image can then be scaled to the science images exposure time since the dark current should be linearly proportional to exposure time. When the detector is capable of being held at precise temperatures, dark images may be taken over multiple hours during the day to produce a high quality master dark image that may then be scaled and subtracted from all subsequent images.

Next, multiplicative noise, such as a CCD's pixel-to-pixel response, should be accounted for. This pixel-to-pixel response should be uniform across the image and to achieve this an average response may be divided out. The average response is referred to as a ‘flat’ image or flat-field and may be acquired by observing a uniformly illuminated surface to determine the pixel-to-pixel response.

Dome flats are images taken of a relatively flat surface, usually the inside a telescopes dome, and are used in both photometry and spectroscopy. The surface is uniformly and indirectly illuminated by a projector lamp, ideal for flat-field images. Alternate flat-fielding methods, such as night sky and twilight flats, are available but are suited solely for photometry. Night sky flats are produced from science images containing mostly sky. The science images are combined using the ‘mode’ statistic which removes any celestial objects at the cost of a low Signal-to-Noise Ratio (S/N) flat-field. Twilight flats are produced from images of the twilight (or dawn) sky. They are taken when the Sun has just set, in the opposite direction, at $\sim 20^\circ$ from zenith and provide a better S/Ns at the cost of careful timing of the images.

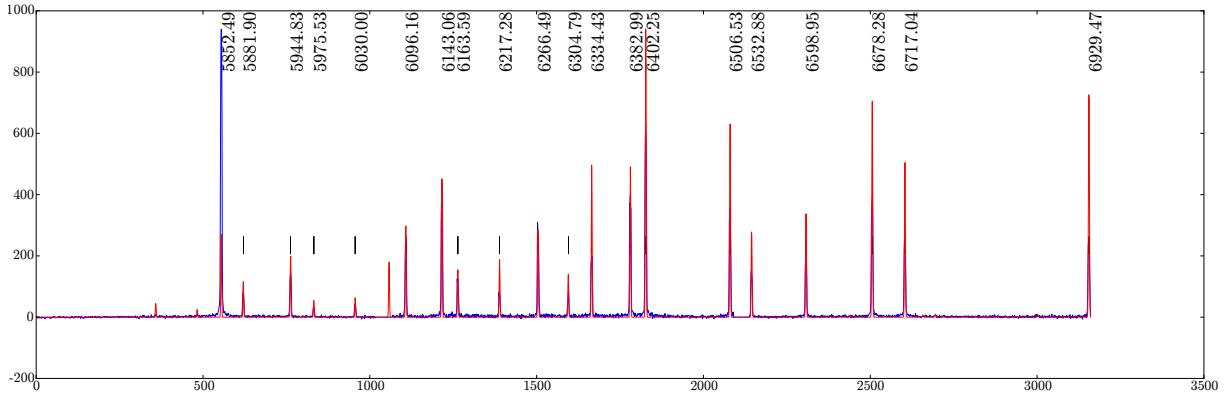


Figure 2.7: Example of an arc spectrum for NeAr taken with SALT’s RSS using the PG1800 grating at a grating angle of 34.625° , an articulation angle of 69.258° , and covering a wavelength range of $\sim 5600 - 6900 \text{ \AA}$. Plot adapted from SALT’s published Longslit Line Atlases, (2023).²

A flat-field must be normalized before being used to correct any science images since it only acts to account for the pixel-to-pixel response and not for the additive errors. A normalized spectroscopic flat image, $F_\lambda^n(x, y)$, can be calculated as:

$$F_\lambda^n(x, y) = \frac{F_\lambda(x, y) - B(x, y) - (\frac{t_S}{t_D})D(x, y)}{\text{med}_{lp}(F_\lambda(x, y) - B(x, y) - (\frac{t_S}{t_D})D(x, y))}, \quad (2.9)$$

where $F_\lambda(x, y)$ is the non-corrected flat image, $B(x, y)$ is the bias image, $D(x, y)$ is the dark image which is scaled by the exposure time of the science image, t_S , and the dark image, t_D . med_{lp} is a low-pass median filter which smoothes out any rapid changes in the pixel-to-pixel response, removing the illumination contribution.

The calibrated science image, $S_\lambda^*(x, y)$, which accounts for the bias and dark currents as well as the flat fielding can then be calculated as:

$$S_\lambda^*(x, y) = \frac{S_\lambda(x, y) - B(x, y) - (\frac{t_S}{t_D})D(x, y)}{F_\lambda^n(x, y)}. \quad (2.10)$$

When multichannel CCDs are used, which consist of multiple CCDs or a CCD with multiple output amplifiers, additional calibrations, specifically cross-talk corrections and mosaicking, are required. Cross-talk noise refers to contamination that occurs during readout in one channel from another channel with a high signal and occurs because the signals can not be completely isolated from one another. Cross-talk corrections therefore account for this signal contamination between channels being read out at the same time (Freyhammer et al., 2001). Mosaicking is necessary for multichannel CCDs since the digitized signal read out from the detector has no reference of the physical location of the pixel it was detected at. Mosaicking, therefore, correctly orients the data acquired from a multichannel detector so that a single correctly oriented image is produced.

Wavelength Calibration

Finally, since the dispersion element breaks the incident light into its constituent wavelengths non-linearly (§ 2.1.7), the relation between the pixel on a detector and the wavelength of the light incident on it is unknown. Ideally, the spectrometer’s optics would be

²NeAr plot sourced from <https://astronomers.salt.ac.za/data/salt-longslit-line-atlas/>

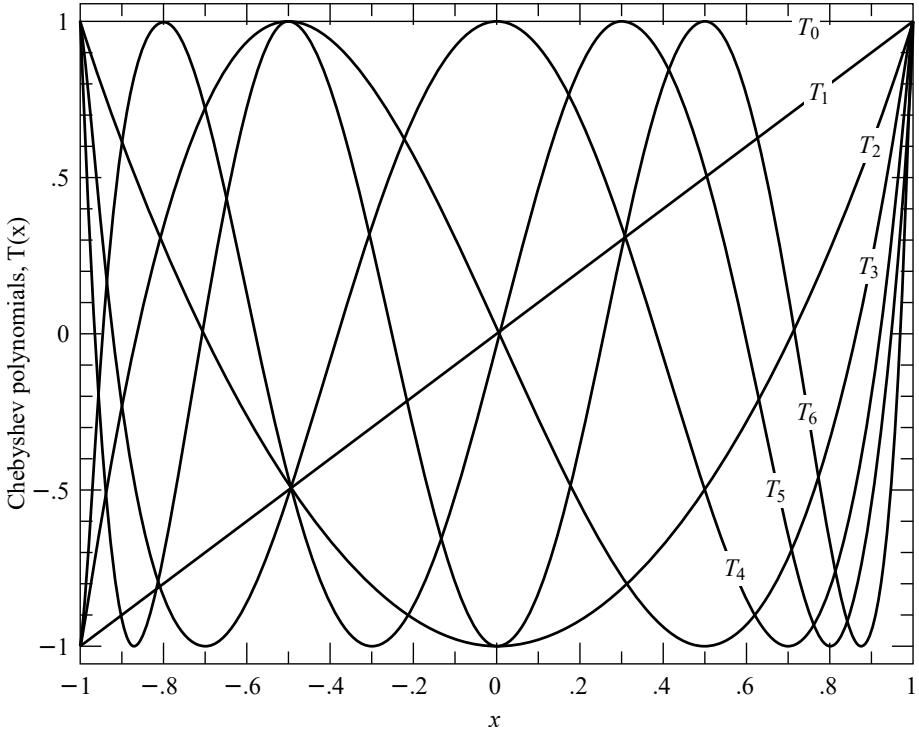


Figure 2.8: The first seven Chebyshev polynomials (T_0 through T_6) as defined by Equation 2.12 over the region $[-1, 1]$ for which they are orthogonal. Plot adapted from (Press et al., 2007) (2023)³

modelled to produce a reliable pixel to wavelength calibration (see E.g. Liu and Hennelly, 2022), but this becomes increasingly more difficult for spectrometers with complex, non-sedentary, optical paths. Alternatively, a source with well-defined spectral features, with said features evenly populating the wavelength region of interest, such as in Figure 2.7 may be observed. The observed frame is commonly referred to as an ‘arc’ frame, after the arc-lamps used to acquire the spectra, and should be observed alongside the science frames over the course of an observation run. It is important that the arc frame is observed at the same observing conditions and parameters as the science frames since the optical path will vary over the course of an observing run and for different observing parameters, invalidating previously acquired arc frames.

The wavelength calibrations then consist of defining a two-dimensional pixel-to-wavelength conversion function from the arc frame which may later be applied to calibrate the science frames. The two most common approximations for wavelength calibrations are the Chebyshev and Legendre polynomial approximations.

Chebyshev polynomials The Chebyshev polynomials are defined explicitly as:

$$T_n(x) = \cos(n \cos^{-1}(x)) , \text{ or recursively as} \quad (2.11)$$

$$\begin{aligned} T_0(x) &= 1 , \\ T_1(x) &= x , \text{ and} \end{aligned} \quad (2.12)$$

$$T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x) , \text{ for } n \geq 1 ,$$

³Excellent resources on Chebyshev and Legendre polynomials are available digitally at www.numerical.recipes/book.

where T is a Chebyshev polynomial of order n .⁴ An important property of Chebyshev polynomials is that they are orthogonal polynomials. This means that the inner product of any two differing Chebyshev polynomials, $T_i(x)$ and $T_j(x)$, over the range $[-1, 1]$ is zero, as shown by:

$$\int_{-1}^1 T_i(x)T_j(x) \frac{1}{\sqrt{1-x^2}} dx = \begin{cases} 0, & i \neq j \\ \pi/2, & i = j \neq 0 \\ \pi, & i = j = 0 \end{cases}, \quad (2.13)$$

where $1/\sqrt{1-x^2}$ is the weighting factor for Chebyshev polynomials. This property is important because it means that the coefficients in the Chebyshev polynomial expansion are independent of one another, allowing for a unique solution when approximating an unknown function (Arfken and Weber, 1999; Press et al., 2007).

An approximation, using Chebyshev polynomials, of an unknown wavelength calibration function is given by:

$$f(x) \approx \sum_{i=0}^N c_i T_i(u), \text{ or} \quad (2.14)$$

$$F(x, y) \approx \sum_{i=0}^N \sum_{j=0}^M c_{ij} T_i(u) T_j(v), \quad (2.15)$$

for a one- or a two-dimensional wavelength surface function, respectively. Here N and M are the desired x and y orders, and c_i and c_{ij} are the Chebyshev polynomial coefficients (Florinsky and Pankratov, 2015; Leng, 1997). Since the orthogonality property of the Chebyshev polynomials only holds true over the range $[-1, 1]$, the $(x, y) \in ([0, a], [0, b])$ pixel coordinates must be remapped to $u, v \in [-1, 1]$ following the relation:

$$(u, v) = \frac{2(x, y) - a - b}{b - a}. \quad (2.16)$$

The Chebyshev polynomials are more suited for wavelength calibrations than standard polynomials since they are orthogonal and have minima and maxima located at $[-1, 1]$, as seen in Figure 2.8. This means that the Chebyshev approximation is exact when $x = x_n$, where x_n are the positions of the $n - 1$ x -intercepts of $T_N(x)$. These properties greatly minimize the error in the Chebyshev approximation, even at lower order approximations (Arfken and Weber, 1999).

Legendre polynomials Similar to the Chebyshev polynomials, the Legendre polynomials may be defined explicitly as:

$$P_n(x) = \frac{1}{2^n n!} \frac{d^n}{dx^n} (x^2 - 1)^n, \text{ or recursively as} \quad (2.17)$$

$$\begin{aligned} P_0(x) &= 1, \\ P_1(x) &= x, \text{ and} \end{aligned} \quad (2.18)$$

$$(n + 1)P_{n+1}(x) = (2n + 1)xP_n(x) - nP_{n-1}(x), \text{ for } n \geq 1,$$

⁴Chebyshev polynomials are denoted T as a hold-over from the alternate spelling of ‘Tchebycheff’.

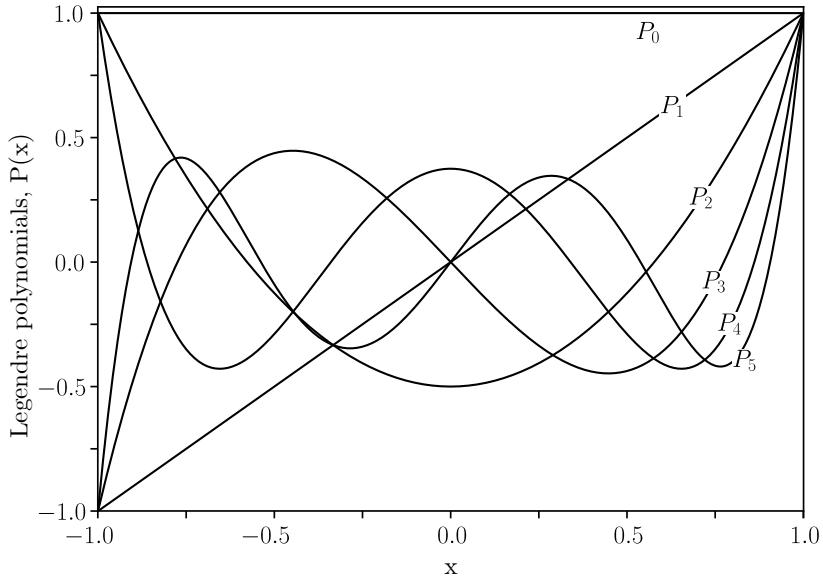


Figure 2.9: The first six Legendre polynomials (P_0 through P_5) as defined by Equation 2.20 over the region $[-1, 1]$ for which they are orthogonal. Plot adapted from Geek3, CC BY-SA 3.0, via Wikimedia Commons (2023).

where P is a Legendre polynomial of order n . Legendre polynomials also hold the property of orthogonality. This means that the inner product of any two differing Legendre polynomials, $P_i(x)$ and $P_j(x)$, over the range $[-1, 1]$ is zero, as shown by:

$$\int_{-1}^1 P_i(x) P_j(x) dx = \begin{cases} 0, & i \neq j \\ \frac{2}{2n+1}, & i = j \end{cases}, \quad (2.19)$$

where a weight of 1 is the weighting factor for Legendre polynomials (Dahlquist and Björck, 2003; Press et al., 2007).

An approximation, using Legendre polynomials, of an unknown wavelength calibration function is given by:

$$f(x) \approx \sum_{n=0}^N a_n P_n(u), \text{ or} \quad (2.20)$$

$$F(x, y) \approx \sum_{i=0}^N \sum_{j=0}^M a_{ij} P_i(u) P_j(v), \quad (2.21)$$

for a one-dimensional wavelength function or a two-dimensional surface function, respectively. Here N and M are the desired x and y orders, u and v are the same mapping variable as in Equation 2.16, and a_{ij} are the Legendre polynomial coefficients.

Legendre polynomials benefit from having the orthogonality condition with no weight necessary ($w = 1$) which makes their coefficients computationally easier to compute but increases the error in a Legendre approximation when compared to that of the error in a Chebyshev approximation for functions of the same order, N (Ismail, 2005).

Regardless of which method of polynomial approximation is chosen, the polynomials are fit by varying the relevant coefficients using the least squares method. The resultant

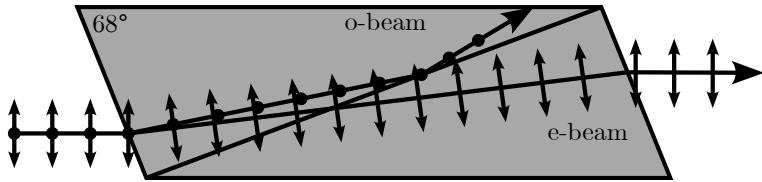


Figure 2.10: Diagram of a Nicol prism for incident non-polarized light. Diagram adapted from Fred the Oyster, CC BY-SA 4.0, via Wikimedia Commons (2023).

minimized function may then be used to convert the science frames from an (x -pixel, y -pixel) coordinate system to a (λ , y -pixel) coordinate system.

2.2 Polarimetry

Both Huygens and Newton came to the conclusion that light demonstrates transversal properties (Huygens, 1690; Newton and Innys, 1730), which was later further investigated and coined as ‘polarization’ by Malus (Malus, 1809). Malus also investigated the polarization effects of multiple materials including some of which were birefringent, such as optical calcite, which he referred to as Iceland spar after Bartholinus’ investigations of the material (Bartholinus, 1670).

Fresnel built on Malus’ work showing that two beams of light, polarized at a right angle to one another, do not interfere, conclusively proving that light is transversal in nature, opposing the widely accepted longitudinal nature of light due to the prevalent belief in the ether. He later went on to correctly describe how polarized light is reflected and refracted at the surface of optical dielectric interfaces, without knowledge of the electromagnetic nature of light. Fresnel’s equations for the reflectance and transmittance, R and T , are defined as:

$$\begin{aligned} R_s &= \left| \frac{Z_2 \cos \theta_i - Z_1 \cos \theta_t}{Z_2 \cos \theta_i + Z_1 \cos \theta_t} \right|^2, \\ R_p &= \left| \frac{Z_2 \cos \theta_t - Z_1 \cos \theta_i}{Z_2 \cos \theta_t + Z_1 \cos \theta_i} \right|^2, \\ T_s &= 1 - R_s, \text{ and} \\ T_p &= 1 - R_p, \end{aligned} \quad (2.22)$$

where s and p are the two polarized components of light perpendicular to one another, Z_1 and Z_2 are the impedance of the two media, and θ_i , θ_t , and θ_r are the angles of incidence, transmission, and reflection, respectively (Fresnel, 1870).

Nicol was the first to create a polarizer, aptly named the Nicol prism, where the incident light is split into its two perpendicular polarization components, namely the ordinary and extraordinary beams. Faraday discovered the phenomenon where the polarization plane of light is rotated when under the influence of a magnetic field, known as the Faraday effect. Brewster calculated the angle of incidence, $\theta_B = \arctan n_2/n_1$, at which incident polarized light is perfectly transmitted through a transparent surface, with refractive indexes of n_1 and n_2 , while non-polarized incident light is perfectly polarized when reflected and partially polarized when refracted.

Stokes’ work created the first consistent description of polarization and gave us the

Stokes parameters which describe an operational approach to measuring polarization (discussed further in § 2.2.1) (Stokes, 1852). Hale was the first to apply polarization to astronomical observations, using a Fresnel rhomb and Nicol prism as a quarter-wave plate and polarizer, respectively (Hale, 1908, 1979). Wollaston also created a prism, similarly named the Wollaston prism, which allowed simultaneous observation of the ordinary and extraordinary beams due to the smaller deviation angle (Wollaston, 1802). Finally, Chandrasekhar's work furthered our understanding of astrophysical polarimetry by explaining the origin of polarization observed in starlight as well as mathematically modeling the polarization of rotating stars, which came to be named Chandrasekhar polarization (Chandrasekhar, 1950).

2.2.1 Polarization

Maxwell's equations for an electromagnetic field propagating through a vacuum are given as:

$$\begin{aligned}\nabla \cdot \mathbf{E} &= 0, \\ \nabla \cdot \mathbf{B} &= 0, \\ \nabla \times \mathbf{E} &= -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}, \text{ and} \\ \nabla \times \mathbf{B} &= \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t},\end{aligned}\tag{2.23}$$

where \mathbf{E} and \mathbf{B} are the electric and magnetic field vectors, and c is the speed of light. In a right-handed (x, y, z) coordinate system, a non-trivial solution of an electromagnetic wave following Maxwell's Equations propagating along the z -axis, towards a hypothetical observer, is described by:

$$\begin{aligned}\mathbf{E} &= E_x \cos(kz - \omega t + \Phi_x) \hat{x} + E_y \cos(kz - \omega t + \Phi_y) \hat{y}, \text{ and} \\ \mathbf{B} &= \frac{1}{c} E_y \cos(kz - \omega t + \Phi_y) \hat{x} + \frac{1}{c} E_x \cos(kz - \omega t + \Phi_x) \hat{y},\end{aligned}\tag{2.24}$$

where E_x , E_y , Φ_x , and Φ_y are all parameters describing the amplitude and phase of the electric field vector in the (x, y) plane, and with the magnetic field vector proportional and perpendicular to the electric field vector (Griffiths, 2005).

Considering only the electric field component and rewriting Equation 2.24 using complex values allows us to simplify the form of the solution to:

$$\mathbf{E} = \Re(\mathbf{E}_0 e^{-i\omega t}),\tag{2.25}$$

where we only consider the real part of the equation, and where \mathbf{E}_0 is defined as:

$$\mathbf{E}_0 = E_x e^{i\Phi_x} \hat{x} + E_y e^{i\Phi_y} \hat{y},\tag{2.26}$$

and is referred to as the polarization vector since it neatly contains the parameters responsible for the polarization properties (Degl'Innocenti, 2014).

For an electric field vector with oscillations in some combination of the x and y axes, the tip of the vector sweeps out an ellipse, as depicted in Figure 2.11. This ellipse is referred to as the polarization ellipse and has the form:

$$\left(\frac{\mathbf{E}_x}{\mathbf{E}_{0,x}} \right)^2 + \left(\frac{\mathbf{E}_y}{\mathbf{E}_{0,y}} \right)^2 - \frac{2\mathbf{E}_x \mathbf{E}_y}{\mathbf{E}_{0,x} \mathbf{E}_{0,y}} \cos \Phi = \sin^2 \Phi,\tag{2.27}$$

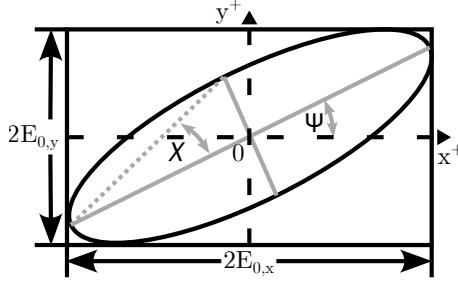


Figure 2.11: The polarization ellipse for an electric field vector propagating through free space. Diagram adapted from Inductiveload, PDM 1.0, via Wikimedia Commons (2023).

where $\Phi = \Phi_x - \Phi_y$ is the phase difference between the x and y phase parameters. The degree of polarization for the polarization ellipse is related to the eccentricity of the ellipse and the angle at which it is rotated relates to the polarization angle. Since $\mathbf{E}_{0,x}$, $\mathbf{E}_{0,y}$, Φ_x , and Φ_y describe the wave, the polarization ellipse that results from these parameters is fixed as the wave continues to propagate.

Since observations consist of images taken over a desired exposure time, time averaging of Equation 2.27 over the exposure time is necessary. Given the periodical nature and high frequencies of the fields, the time averaging may be found over a single oscillation using:

$$\langle \mathbf{E}_i \mathbf{E}_j \rangle = \lim_{dt \rightarrow \infty} \frac{1}{T} \int_0^T \mathbf{E}_i \mathbf{E}_j dt, \quad \text{for } i, j \in (x, y), \quad (2.28)$$

where T is the total averaging time over the electric field vectors \mathbf{E}_i and \mathbf{E}_j (Collett, 2005). Applying the time averaging to Equation 2.27 and simplifying results in:

$$(E_{0x}^2 + E_{0y}^2)^2 - (E_{0x}^2 - E_{0y}^2)^2 - (2E_x E_y \cos \Phi)^2 = (2E_x E_y \sin \Phi)^2. \quad (2.29)$$

The expressions inside the parentheses can be found through observation and may also be represented as:

$$\mathbf{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} E_{0x}^2 + E_{0y}^2 \\ E_{0x}^2 - E_{0y}^2 \\ 2E_{0x} E_{0y} \cos \Phi \\ 2E_{0x} E_{0y} \sin \Phi \end{pmatrix}, \quad (2.30)$$

where S_0 to S_3 are referred to as the Stokes (polarization) parameters. The parameters describe the: S_0 , total intensity (often normalized to 1); S_1 , ratio of the Linear Horizontally Polarized (LHP) to Linear Vertically Polarized (LVP) light; S_2 , ratio of the Linear $+45^\circ$ Polarized ($L+45^\circ$) to Linear -45° Polarized ($L-45^\circ$) light; and S_3 , ratio of the Right Circularly Polarized (RCP) (clockwise) to Left Circularly Polarized (LCP) (counter-clockwise) light. When the intensity is normalized, the Stokes parameters range from 1 to -1 , based on the dominating component of the parameter (Chandrasekhar, 1950; Stokes, 1852).

From Equation 2.29 and 2.30, the polarization parameters are related by:

$$I^2 = Q^2 + U^2 + V^2, \quad (2.31)$$

for entirely polarized light. Only beams of completely polarized light could be accounted for before Stokes' work on polarization. Using the Stokes parameters, we can now account

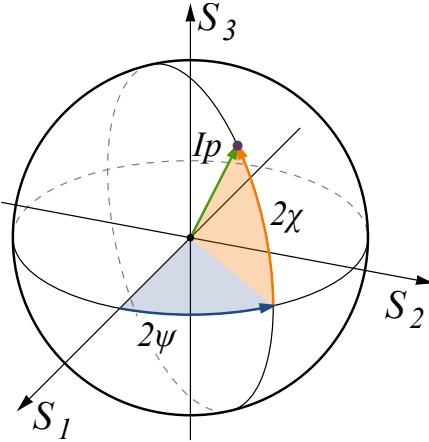


Figure 2.12: The Poincaré sphere describing the polarization properties of a wave-packet propagating through free space. Diagram adapted from Inductiveload, PDM 1.0, via Wikimedia Commons (2023).

for partially polarized light such that:

$$I^2 \geq Q^2 + U^2 + V^2, \quad (2.32)$$

where I , Q , U , and V are the normalized polarization parameters, often symbolized as

$$\bar{Q} = \frac{Q}{I}, \quad \bar{U} = \frac{U}{I}, \quad \text{and} \quad \bar{V} = \frac{V}{I}. \quad (2.33)$$

Similar to the polarization ellipse, the Stokes parameters may be depicted using the Poincaré sphere in spherical coordinates $(IP, 2\Psi, 2\chi)$, such that:

$$\begin{aligned} I &= S_0, \\ P &= \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}, \text{ for } 0 \leq P \leq 1, \\ 2\Psi &= \arctan \frac{S_3}{\sqrt{S_1^2 + S_2^2}}, \text{ and} \\ 2\chi &= \arctan \frac{S_2}{S_1}, \end{aligned} \quad (2.34)$$

where I denotes the total intensity, P denotes the degree of polarization, or the ratio of polarized to non-polarized light in the wave-packet, χ denotes the polarization angle, and Ψ denotes the ellipticity angle of the polarization ellipse.

2.2.2 Polarization Measurement

Except for polarimetry in the radio-wavelength regime, the polarization of a beam can not be directly measured. The polarization properties may, however, be recovered from the beam through the manipulation of the four parameters given in Equation 2.24. This so-called manipulation is achieved by passing the beam through optical elements which vary the beam for differing amplitudes and phases. These matrix operations may be represented by their corresponding Mueller matrices.

For ideal components, the resultant beam \mathbf{S}' after passing through an optical element is given by $\mathbf{S}' = \mathbf{MS}$, where \mathbf{S} is the beam incident on the optical element and \mathbf{M}

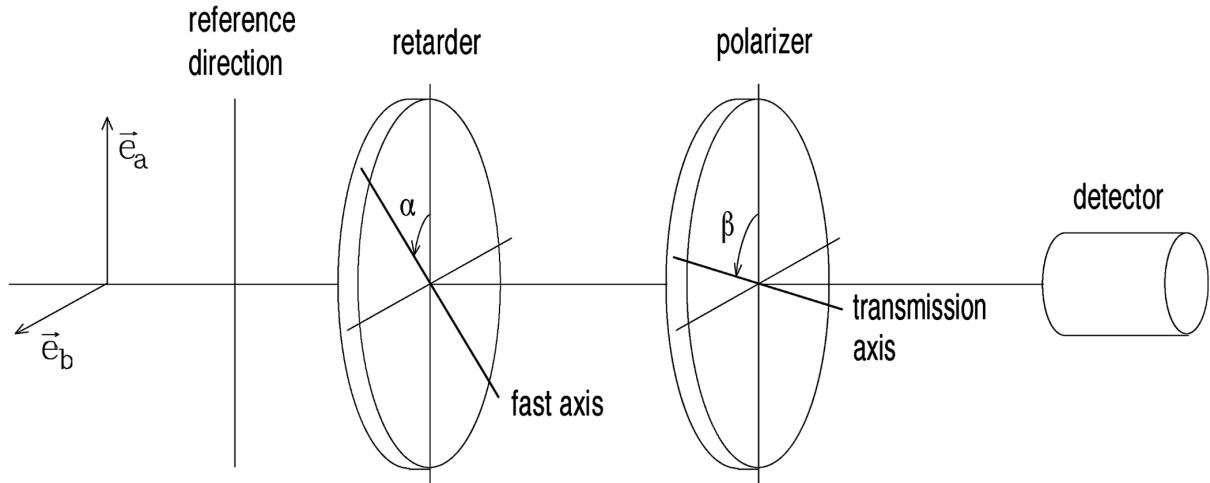


Figure 2.13: A diagram of an ideal polarimeter. Diagram adapted from Degl'Innocenti and Landolfi (2004).

represents the 4×4 Mueller matrix representing the optical element. Mueller matrices are especially useful when dealing with paths through optical elements as they observe the ‘train’ property (Priebe, 1969). This means that an incoming beam \mathbf{S} passing, in order, through elements with known Mueller matrices ($\mathbf{M}_0, \dots, \mathbf{M}_N$) results in an outgoing beam \mathbf{S}' such that:

$$\mathbf{S}' = \mathbf{M}_N \dots \mathbf{M}_0 \mathbf{S}. \quad (2.35)$$

Some Mueller Matrices are given below with angles related to those in Figure 2.13, measured counter-clockwise in a right-handed coordinate system.

General rotation The Mueller matrix for coordinate space rotations about the origin by an angle θ ,

$$\mathbf{R}(\theta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\theta & \sin 2\theta & 0 \\ 0 & -\sin 2\theta & \cos 2\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (2.36)$$

General linear retardance The Mueller matrix for retardance where α is the angle between the incoming vector and fast axis, and δ is the retardance introduced by the retarder,

$$\mathbf{W}(\alpha, \delta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2 2\alpha + \sin^2 2\alpha \cos \delta & \cos 2\alpha \sin 2\alpha(1 - \cos \delta) & \sin 2\alpha \sin \delta \\ 0 & \cos 2\alpha \sin 2\alpha(1 - \cos \delta) & \cos^2 2\alpha \cos \delta + \sin^2 2\alpha & -\cos 2\alpha \sin \delta \\ 0 & -\sin 2\alpha \sin \delta & \cos 2\alpha \sin \delta & \cos \delta \end{bmatrix}. \quad (2.37)$$

The retarder is often referred to by this retardance, e.g. if the retardance is $\delta = \pi$ or $\pi/2$, the retarder is referred to as a half- or quarter-wave plate, respectively.

General linear polarization The Mueller matrix for linear polarization where β is the angle between the incoming vector and transmission axis,

$$\mathbf{P}(\beta) = \frac{1}{2} \begin{bmatrix} 1 & \cos 2\beta & \sin 2\beta & 0 \\ \cos 2\beta & \cos^2 2\beta & \cos 2\beta \sin 2\beta & 0 \\ \sin 2\beta & \sin 2\beta \cos 2\beta & \sin^2 2\beta & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}. \quad (2.38)$$

These matrices in combination with Equation 2.35 allow us to describe how the incoming Stokes parameters would change when passing through the various optical elements. For a setup similar to Figure 2.13, the detected Stokes parameters can be described by:

$$\begin{aligned} S'(\alpha, \beta, \gamma) \propto \frac{1}{2} \{ & I + [Q \cos 2\alpha + U \sin 2\alpha] \cos(2\beta - 2\alpha) \\ & - [Q \sin 2\alpha + U \cos 2\alpha] \sin(2\beta - 2\alpha) \cos \gamma \\ & + V \sin(2\beta - 2\alpha) \sin \gamma \}, \end{aligned} \quad (2.39)$$

where the retardance angle, α , polarization angle, β , for a wave plate with a relative phase difference, γ , may be varied to acquire a system of equations that can be solved to retrieve the Stokes polarization parameters (Bagnulo et al., 2009).

Several or more frames taken under differing configurations may be used to reduce a system of equations to extract all four Stokes polarization parameters, but it is possible to extract the I , Q and U polarization parameters using only four frames, or two dual-beam frames, for well-chosen configurations and assuming ideal components. This ideal configuration varies the retarder angle such that $\Delta\alpha = \pi/8$ while keeping the polarizer stationary. More frames for additional retarder angles are advisable and often necessary, however, as they correct for any differences in sensitivity, such as may arise in a polarized flat field and which is further discussed in § 2.2.3 (Patat and Romaniello, 2006).

From Equation 2.39 we see that the linear retarder element is the driving element of a polarizer as the first three Stokes parameters (S_{0-2} , or I , Q , and U) may be found by changing only the angle of retardance, α .

Wave plates Wave plates, also commonly referred to as retarders, are generally made from optically transparent birefringent crystals. A wave plate has a fast and slow axis, which are perpendicular to one another and both perpendicular to an incident beam. Due to the birefringence of the wave plate medium, the phase velocity of the beam polarized parallel to the fast axis, namely the extraordinary beam, slightly increases while that of the beam polarized parallel to the slow axis, namely the ordinary beam, remains unaffected. This difference in the perpendicular component's phase velocities introduces a relative phase difference between the two beams, γ , which is given by:

$$\gamma = \frac{2\pi\Delta n L}{\lambda_0} \quad (2.40)$$

where Δn and L refer to the birefringence and thickness of the wave plate medium, respectively, and λ_0 refers to the vacuum wavelength of the beam (Hecht, 2017).

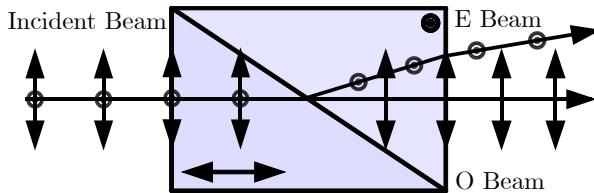


Figure 2.14: Diagram of a Rochon prism. Included in the diagram are the optical axes of the differing sections of the birefringent material as well as polarizing directions of the incident beam, denoted using the \leftrightarrow and \odot symbols, for the O - and E -beams, respectively. Figure adapted from ChrisHedgesUK, CC BY-SA 3.0, via Wikimedia Commons (2023).

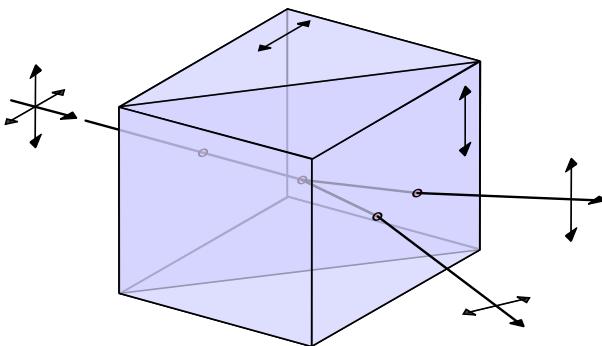


Figure 2.15: Diagram of a Wollaston prism. Included in the diagram are the optical axes of the differing sections of the birefringent material as well as polarizing directions of the incident beam, denoted using the \leftrightarrow and \ddagger symbols, for the O - and E -beams, respectively. Diagram adapted from fgalore, CC BY-SA 3.0, via Wikimedia Commons (2023).

This relative phase difference determines the name of the wave plate, such that the $\gamma = m(\pi/2)$ and $\gamma = m(\pi/4)$ phase differences, for $m \in \mathbb{Z}^+$, refer to the half- and quarter-wave plates (which are the most common wave plate phases), respectively. Phase differences with an integer multiple of one another relate to the same phase difference and are referred to as multiple-order wave plates, while wave plates with a phase difference less than an integer multiple are referred to as zero-order wave plates. Several multiple-order wave plates can be combined by alternatively aligning the fast axis of one to the slow axis of another to create a compound zero-order wave plate (Hale and Day, 1988).

Polarizers Polarizers are typically made from two prisms, of a birefringent material, cemented together with an optically transparent adhesive. The actual effect of separating the perpendicular polarization components is achieved using varying effects, namely through:

- absorption of one of the polarized components, such as in Polaroid polarizing filters,
- total internal reflection of a single polarized component, such as in a Nicol prism (Figure 2.10),
- Refraction of a single polarized component, such as in a Rochon prism (Figure 2.14), or
- Refraction of both polarization components in differing directions, such as in a Wollaston prism (Figure 2.15).

Wollaston prisms The Wollaston prism consists of two right-angle prisms consisting of a birefringent monoaxial material, cemented together with an optically transparent adhesive along their hypotenuses with their optical axes orthogonal, as seen in Figure 2.15. The Wollaston prism is a common optical polarizing element in astrophysical polarimetry

which separates an incident beam into two linearly polarized *O*- and *E*-beams, orthogonal to one another, and deviated from their common axis equally. The deviation angle of the polarized beams is determined by the wedge angle which is defined as the angle from the common hypotenuse to that of the outer transmission face of either prism.

Wollaston prisms benefit over simpler elements (such as those listed in the polarizer paragraph) since a single frame allows for the observation of both orthogonal polarization components. This halves the observational time required to collect enough data to calculate the Stokes parameters, at the cost of an increase in calibration and reduction difficulty (Simon, 1986).

2.2.3 Polarimetric calibrations

The raw science images acquired during polarimetric observations contain a combination of useful science data as well as noise, similar to § 2.1.8. Corrections and calibrations related to the detector remain unchanged from those described in § 2.1.8, while those related to correcting for the optical elements relate to corrections for spurious polarization effects.

Flat Fielding

Once the CCD calibrations have been completed, the polarization intrinsic to the optical elements needs to be accounted for such that the pixel-to-pixel response is made uniform. Flat-fielding is, once again, used to correct for this. The flats taken for polarimetry, however, introduce an additional challenge as the targets for conventional flats are polarized, such as twilight and dome flats which are polarized by light scattering in the atmosphere and the reflective surface of the dome, respectively.

If no unpolarized flat images can be taken for flat field calibrations then, when possible due to the polarimeter design, the wave plate may be constantly rotated to act as a depolarizing element; this is effective so long as the wave plate rotation period is much faster than the flat's exposure time. Alternatively, polarized flats may be taken at the same set of half-wave plate angles used for science observations and averaged together to achieve a similar depolarizing effect.

Observing additional ‘redundant’ exposures for the science and flat images increases the depolarizing effect up to the maximum of 16 half-wave plate positions, where exposures with a half-wave plate angle differing by $\pi/4$ from another are considered redundant due to the *O*- and *E*-beams swapping between the related exposures.

Increasing the amount of redundant observations proportionally increases the time needed to observe all the exposures, which in turn introduces time-dependent effects such as fringing or intensity variations of the flat source. As such, a middle ground must be found for the amount of redundant frames observed. (Patat and Romanielo, 2006; Peinado et al., 2010).

Dual-beam Extraction and Alignment

After calibrations for the CCD and light path are accounted for, the O - and E -beams can be extracted and further reduced. The extraction depends heavily on the layout of the polarimeter but often a simple cropping of the differing sections is enough to separate the two images.

After extracting the O - and E -beams for a specific half-wave plate angle, the images need to be aligned such that the sources present in them overlap. The Wollaston prism needs to be corrected for as it introduces a beam deviation which differs across both images. The aligning of the O - and E -beams is crucial as the comparison of the dual images is what allows for the calculation of the polarization properties.

Sky Subtraction

The polarization introduced by the sky introduces a difference in the intensity of the background sky and needs to be removed as it will influence the polarization results of the target source. Thankfully, the background polarization is an additive type of noise and may be subtracted out across the frames. This subtraction is done independently for both beams in a frame and for each frame since the background intensity of all observed polarimetric beams will differ based on the observational parameters.

2.3 Spectropolarimetry

As the name suggests, spectropolarimetry is the measurement of the polarization of light for a chosen spectral range and provides polarimetric results as a function of wavelength. As spectropolarimetry is so closely reliant on both spectroscopy and polarimetry, advancements in spectropolarimeters have always been gated by the advancements of spectrometers and polarimeters (as described in § 2.1 and § 2.2).

The most notable historical contributions of spectropolarimetry are those of spectropolarimetric studies instead of instrumental developments. Spectropolarimetry provides further insights into a materials physical structure, chemical composition, and magnetic field, allowing spectropolarimetry to be useful across multiple disciplines. In astronomy in particular, spectropolarimetry has been used to study the magnetic field, chemical composition, and underlying structure and emission processes of multiple types of celestial objects (see for example Antonucci and Miller, 1985; Donati et al., 1997; Wang and Wheeler, 2008).

Along with common points of consideration when developing any instrumentation for observational astronomy, such as resolution and sensitivity, spectropolarimeters need also consider the spectral response of the polarimetric components as well as the polarization response of the spectroscopic components as both are simultaneously in the light-path during observations and have noticeable affects on one another. Time is another constraint for spectropolarimetry as the incident light is separated both by wavelength and by polarization states. This division of the incident light results in increased exposure times for both target observations and observations necessary for calibrations.

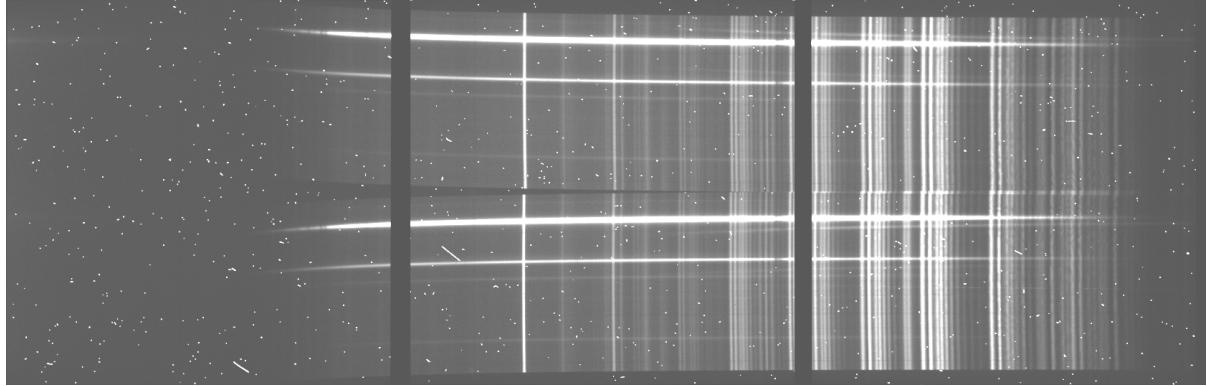


Figure 2.16: A spectropolarimetric target exposure as observed by the SALT RSS in spectropolarimetry mode.

Figure 2.16 illustrates a typical science image taken with a spectropolarimeter. The image contains the O - and E -beams which are both dispersed into their spectra. Spectropolarimetric results are acquired from measurements and calibrations of these images alongside any necessary calibration images.

2.3.1 Spectropolarimetric measurement

The derived relations given in § 2.2.1, such as the Stokes parameters, describe polarization in general and are valid for both polarimetry and spectropolarimetry. Due to the time averaging of the observed light (Equation 2.28), any minor temporal variation, partial polarization, or monochromatic nature of the spectropolarimetric polarization parameters are accounted for.

For linear spectropolarimetry using a dual-beam polarizing element, an exposure measures the O - and E -beam wavelength dependent intensities, $f_{O,i}(\lambda)$ and $f_{E,i}(\lambda)$, for a given wave plate angle θ_i at angle i . These intensities thus relate to the wavelength dependent Stokes parameters as:

$$\begin{aligned} f_{O,i}(\lambda) &= \frac{1}{2}[I(\lambda) + Q(\lambda) \cos(4\theta_i) + U(\lambda) \sin(4\theta_i)], \text{ and} \\ f_{E,i}(\lambda) &= \frac{1}{2}[I(\lambda) - Q(\lambda) \cos(4\theta_i) - U(\lambda) \sin(4\theta_i)]. \end{aligned} \quad (2.41)$$

At least four linear equations are required to solve for three variables in a system of linear equations and thus at least two exposures must be taken to solve for the linear ($I(\lambda)$, $Q(\lambda)$, and $U(\lambda)$) polarization parameters (Degl’Innocenti et al., 2006; Keller, 2002).

The first Stokes parameter, $I(\lambda)$, may be recovered for each dual-beam exposure using

$$I_i(\lambda) = f_{O,i}(\lambda) + f_{E,i}(\lambda). \quad (2.42)$$

By calculating the $I_i(\lambda)$ Stokes parameter for each wave plate position i , the variation of the target over the course of observation may be corrected for, resulting in the $I(\lambda)$ Stokes parameter.

Next, the $Q(\lambda)$ and $U(\lambda)$ Stokes parameters are found by first defining the normalized

difference in relative intensities, $F_i(\lambda)$, as:

$$F_i(\lambda) \equiv \frac{f_{O,i}(\lambda) - f_{E,i}(\lambda)}{f_{O,i}(\lambda) + f_{E,i}(\lambda)}, \quad (2.43)$$

which allows Equation 2.41 to be written, as

$$F_i(\lambda) = \bar{Q}(\lambda) \cos(4\theta_i) + \bar{U}(\lambda) \sin(4\theta_i) = P \cos(4\theta_i - 2\chi), \quad (2.44)$$

in terms of the normalized Stokes parameters, or, alternatively, the degree of polarization, P , and polarization angle, χ (as described in Equation 2.33 and 2.34).

The optimal change in wave plate angle is $\Delta\theta_i = \pi/8$ as it allows the normalized Stokes polarization parameters to be calculated as:

$$\begin{aligned} \bar{Q}(\lambda) &= \frac{2}{N} \sum_{i=0}^{N-1} F_i(\lambda) \cos\left(\frac{\pi}{2}i\right), \text{ and} \\ \bar{U}(\lambda) &= \frac{2}{N} \sum_{i=0}^{N-1} F_i(\lambda) \sin\left(\frac{\pi}{2}i\right), \end{aligned} \quad (2.45)$$

where N is the number of exposures taken, limited such that $N \in [2, 16]$ (Patat and Romaniello, 2006).

2.3.2 Spectropolarimetric calibrations

Just as the elements of a spectropolarimeter are an amalgamation of both a spectrometer and polarimeter, it naturally follows that the calibrations necessary to reduce spectropolarimetric data are a combination of the calibrations needed for spectroscopy and polarimetry, discussed further in § 2.1.8 and § 2.2.3. Even though the spectrometer and polarimeter components both have an effect on an incident beam following the light-path through the spectropolarimeter, the calibration procedures for both methods remain mostly independent of one another and as such need not be repeated here.

Spectropolarimetric calibrations are, however, more involved when compared to the same calibrations for either spectroscopy or polarimetry. Minor deviations in the calibrations across both the spectra and the polarized beam compound, especially when dealing with the wavelength calibration, resulting in poor Signal-to-Noise Ratio (S/N)'s. Generally, more exposures over longer timespans are required to acquire enough redundancy and signal for the calculation of the Stokes parameters on top of the time necessary for calibrations to be completed. It should therefore be noted just how important the calibrations are when dealing with spectropolarimetry.

2.4 The Southern African Large Telescope

Southern African Large Telescope (SALT) is a 10 m class optical/near-infrared telescope situated at the South African Astronomical Observatory (SAAO) field station near Sutherland, South Africa (Burgh et al., 2003). The operational design was based on the Hobby-Eberly Telescope (HET) situated at McDonald Observatory, Texas, which limits

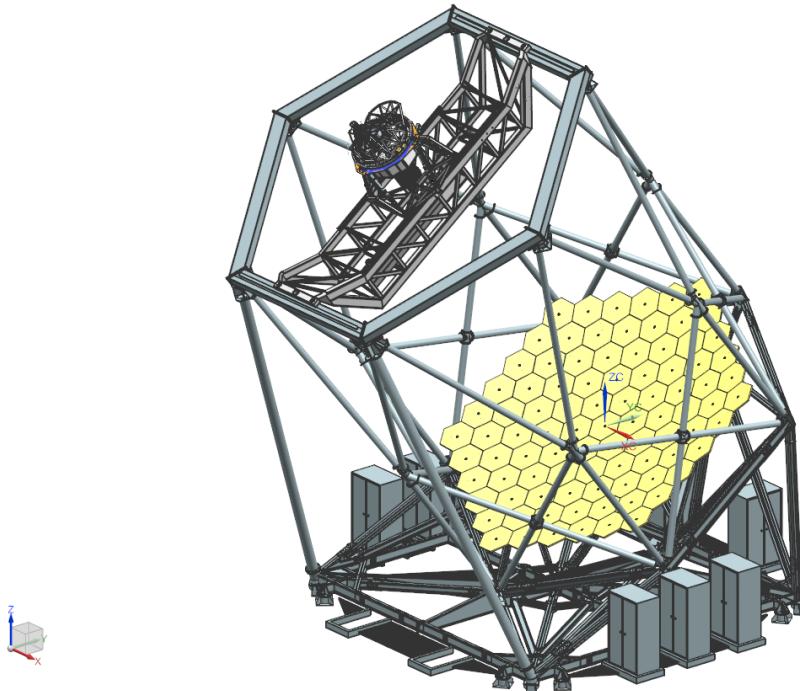


Figure 2.17: The tracker, supporting structure, and primary mirror of SALT. Figure adapted from the SALT call for proposals (2022).⁵

the pointing of the telescope’s primary mirror to a fixed elevation (37° from zenith in the case of SALT) while still allowing for full azimuthal rotation (Ramsey et al., 1998). Both SALT and HET utilize a spherical primary mirror which is stationary during observations and a tracker housing most of the instrumentation that tracks the primary mirrors spherically shaped focal path. Figure 2.17 depicts SALT’s tracker (top left), supporting structure, and primary mirror (bottom right).

2.4.1 The primary mirror

The primary mirror is composed of 91 individual 1 m hexagonal mirrors which together form an 11 m segmented spherical mirror. Each mirror segment can be adjusted by actuators allowing the individual mirrors to approximate a single monolithic spherical mirror. The fixed elevation means that SALT’s primary mirror has a fixed gravity vector allowing for a lighter, cost-effective supporting structure when compared to those of a more traditional altitude-azimuthal mount but with the trade-off that the control mechanism and tracking have increased complexity (Buckley et al., 2006).

2.4.2 Tracker and tracking

During observations the primary mirror is stationary and the tracker tracks celestial objects across the sky by moving along the primary focus. The tracker is capable of 6 degrees of freedom with an accuracy of $5 \mu\text{m}$ and is capable of tracking $\pm 6^\circ$ from the optimal central track position. Targets at declinations from 10.5° to -75.3° , as shown in Figure 2.18 are accessible during windows of opportunity. As the tracker moves along the track the effective collecting area varies and thus SALT has a varying effective diameter

⁵http://pysalt.salt.ac.za/proposal_calls/current/ProposalCall.html

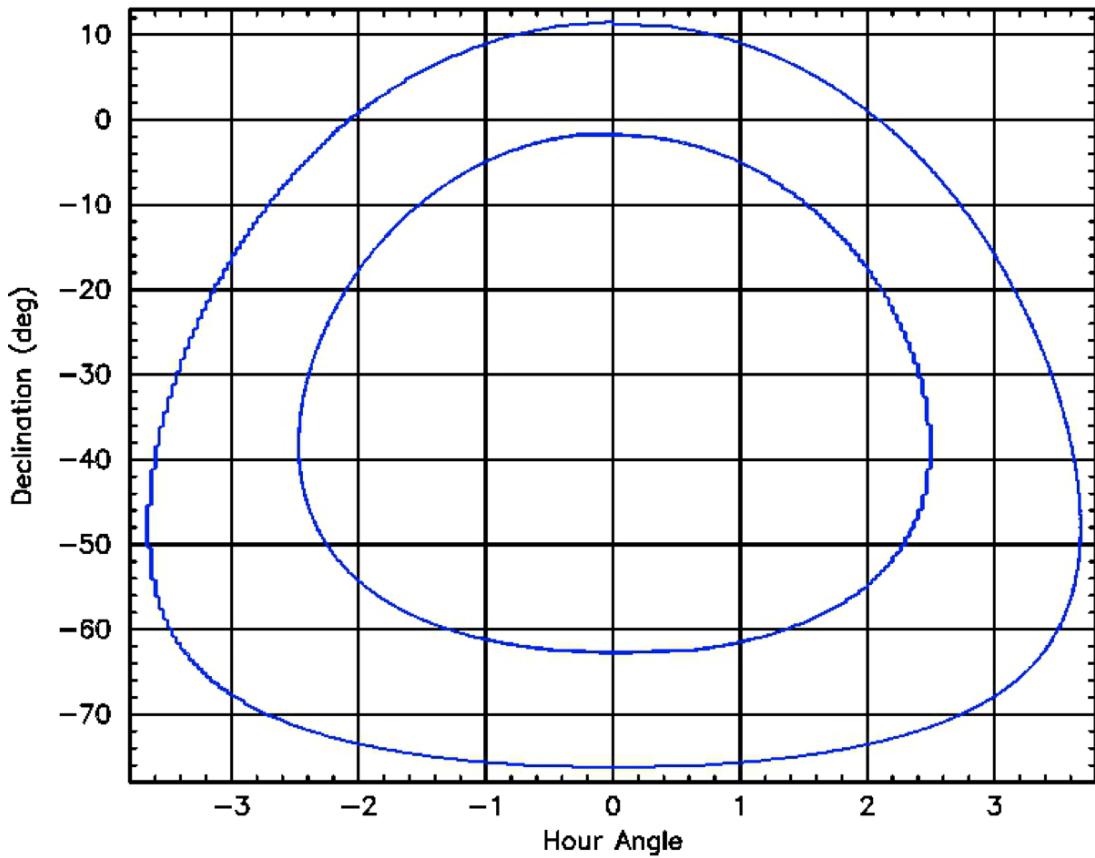


Figure 2.18: The visibility annulus of objects observable by SALT. Figure adapted from the SALT call for proposals (2013).⁶

of ~ 7 m to 9 m when the tracker is furthest and closest to the optimal central position, respectively.

The tracker is equipped with a spherical aberration corrector (O'Donoghue, 2000), and an atmospheric dispersion compensator (O'Donoghue, 2002), which corrects for the spherical aberration caused by the geometry of the primary mirror and allows access to wavelengths as short as 3200 Å. These return a corrected flat focal plane with an 8' diameter field of view at prime focus on to the science instruments, with a 1' annulus around it used by the Tracker in a closed-loop guidance system.

2.4.3 SALT Instrumentation

SALT is equipped with the SALT Imaging Camera (SALTICAM) and the RSS science instruments onboard the tracker, and the High Resolution Spectrograph (HRS) and Near Infra-Red Washburn Labs Spectrograph (NIRWALS) science instruments which are fibre-fed from the tracker to their own climate controlled rooms. The RSS is currently the only instrument used for spectropolarimetry.

⁶https://pysalt.salt.ac.za/proposal_calls/2013-2/

⁷https://pysalt.salt.ac.za/proposal_calls/current/ProposalCall.html

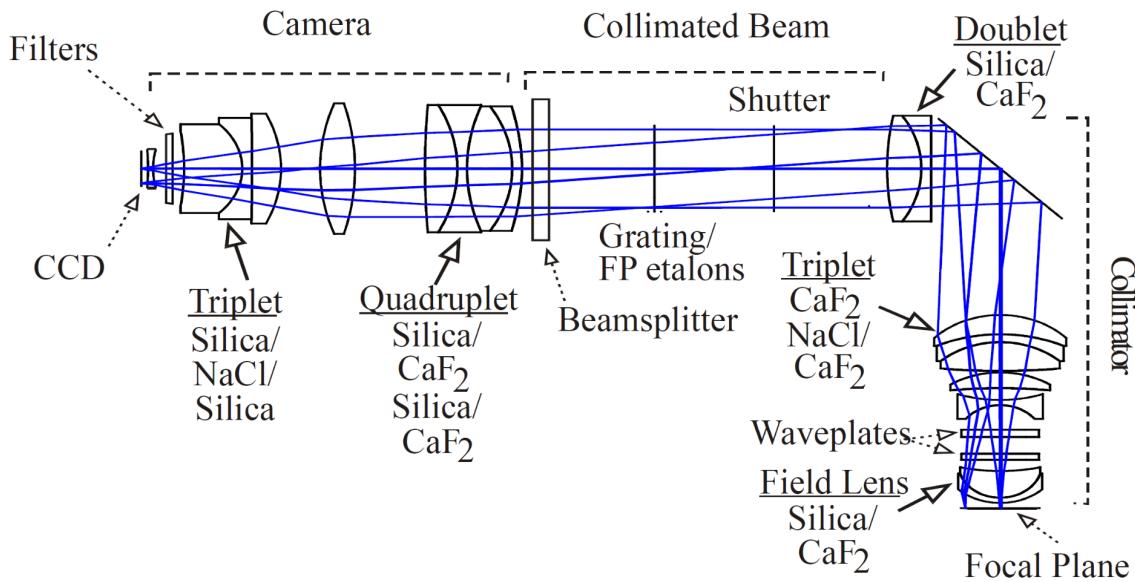


Figure 2.19: The optical path of the SALT RSS. Figure adapted from the SALT call for proposals (2023).⁷

NIRWALS

The Near Infra-Red Washburn Labs Spectrograph (NIRWALS) is currently being commissioned and will have a wavelength coverage of 8000 to 17000 Å, providing medium resolution spectroscopy at $R = 2000$ to 5000 over Near Infra-Red (NIR) wavelengths (Brink et al., 2022; Wolf et al., 2022). NIRWALS is fibre-fed from its integral field unit, containing 212 object fibers, along with a separate sky bundle, containing 36 fibers, housed in the SALT fibre instrument feed. It is ideally suited for studies of nearby galaxies.

HRS

The High Resolution Spectrograph (HRS) echelle spectrograph was designed for high resolution spectroscopy at $R = 37000$ - 67000 covering a wavelength range of 3700 - 8900 Å and consists of a dichroic beam splitter and two VPH gratings (Nordsieck et al., 2003). This instrument is capable of stellar atmospheric and radial velocity analysis.

SALTICAM

The SALT Imaging Camera (SALTICAM) functions as the acquisition camera and simple science imager with various imaging modes, such as full-mode and slot-mode imaging, and supports low exposure times, down to 50 ms (O'Donoghue et al., 2006). This enables photometry of faint objects, especially at fast exposure times.

RSS

The Robert Stobie Spectrograph (RSS) functions as the primary spectrograph on SALT and can operate in long-slit spectroscopy and spectropolarimetry modes, a narrowband imaging mode, and multi-object and high resolution spectroscopy modes (for an in-depth

Grating Name	Wavelength Coverage (Å)	Usable Angles (°)	Bandpass per tilt (Å)	Resolving Power (1.25'' slit)
PG0300 ⁸	3700 – 9000		3900/4400	250 – 600
PG0700 ⁸	3200 – 9000	3.0 – 7.5	4000 – 3200	400 – 1200
PG0900	3200 – 9000	12 – 20	~ 3000	600 – 2000
PG1300	3900 – 9000	19 – 32	~ 2000	1000 – 3200
PG1800	4500 – 9000	28.5 – 50	1500 – 1000	2000 – 5500
PG2300	3800 – 7000	30.5 – 50	1000 – 800	2200 – 5500
PG3000	3200 – 5400	32 – 50	800 – 600	2200 – 5500

Table 2.1: Gratings available for use with the RSS. Table adapted from the SALT call for proposals (2023).

discussion on operational modes see Kobulnicky et al., 2003, or the latest call for proposals).

The Detector The RSS detector consists of a mosaic of 3 CCD chips with a total pixel scale of $0.1267''$ per unbinned pixel with varying readout times depending on the binning and readout mode. The mosaicking results in a characteristic double ‘gap’ in the frames and resultant spectra taken with the RSS, as seen in Figure 2.16.

The Available Gratings The RSS is equipped with a rotatable magazine of six VPH gratings, as listed in Table 2.1. Observations may be planned using simulator tools provided by SALT and are performed in the first order only. The RSS has a clear filter, as well as three Ultraviolet (UV) (with differing lower filtering ranges) and one blue order blocking filter available, used in conjunction with the various gratings to block out contamination from the second order.

RSS Spectropolarimetry Spectropolarimetry using the RSS is currently commissioned for long-slit linear spectropolarimetry, (I, Q, U), where observations are taken following the waveplate pattern lists as in Table 2.2. Circular, (I, V), and all-Stokes, (I, Q, U, V), spectropolarimetry modes are in commissioning with observations including redundant half-wave plate pairs to be commissioned thereafter.⁹

⁸The PG0300 surface relief grating has been replaced with the PG0700 VPH grating as of November 2022 but has been included here as observations using the PG0300 are used in later sections.

⁹Commission status sighted from the latest ‘Polarimetry Observers Guide’ (2024).

Linear ($^{\circ}$)		Linear-Hi ($^{\circ}$)		Circular ($^{\circ}$)		Circular-Hi ($^{\circ}$)		All Stokes ($^{\circ}$)	
$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{4}$
0	-	0	-	0	45	0	45	0	0
45	-	45	-	0	-45	0	-45	45	0
22.5	-	22.5	-			22.5	-45	22.5	0
67.5	-	67.5	-			22.5	45	67.5	0
	-	11.25	-			45	45	0	45
	-	56.25	-			45	-45	0	-45
	-	33.75	-			67.5	-45		
		78.75	-			67.5	45		

Table 2.2: Spectropolarimetry waveplate patterns defined for the RSS. The stated angles refer to the angle of the half ($\frac{1}{2}$ -) and quarter ($\frac{1}{4}$ -) waveplate's optical axis from the perpendicular of the dispersion axis. Table adapted from the SALT call for proposals (2023).

Chapter 3

Existing and Developed Software: An overview of POLSALT, IRAF, and STOPS

This chapter contains an overview of POLSALT (§ 3.1) and the limitations faced during POLSALT wavelength calibrations (§ 3.1.8), a brief overview of the IRAF tasks relevant to spectropolarimetric wavelength calibrations (§ 3.2), and an overview of STOPS, the software developed to supplement the POLSALT reduction process (§ 3.3). Finally, a discussion of the updated reduction process, an example of which may be found in Appendix I, is included (§ 3.4).

3.1 POLSALT - Polarimetric reductions for SALT

POLSALT is developed by SALT and is the official reduction pipeline for spectropolarimetric data taken using the SALT RSS.¹ The newest version of the software, aptly named the ‘beta version’ (‘version’ 23 January 2020), includes a GUI as well as limited interactivity during key steps in the reduction process and was the version adapted in this study.²

The steps that make up the POLSALT reduction pipeline include basic CCD reductions, wavelength calibrations, background subtraction and spectral extraction, raw Stokes calculations, final Stokes calculations, and visualization of the results. Accurate reductions in each step are crucial for accurate results and thus briefly discussed below. Further details for the reduction process may be found at the POLSALT GitHub wiki.³

3.1.1 Basic CCD reductions

Basic CCD reductions are run via `imred.py` and apply the necessary basic reductions to the raw data before any calibrations are applied. These reductions include overscan subtractions, gain corrections, crosstalk corrections, and mosaicking as well as attaching

¹POLSALT is made freely available via the POLSALT GitHub repository, available at <https://github.com/saltastro/polsalt>. It is strongly advised to follow the wiki for installation instructions.

²Installation files and instructions for the ‘beta version’ utilizing the GUI are available at <http://www.saao.ac.za/~ejk/polsalt/code/> in a TAR GZIP file.

³The GitHub wiki for POLSALT is available at <https://github.com/saltastro/polsalt/wiki>.

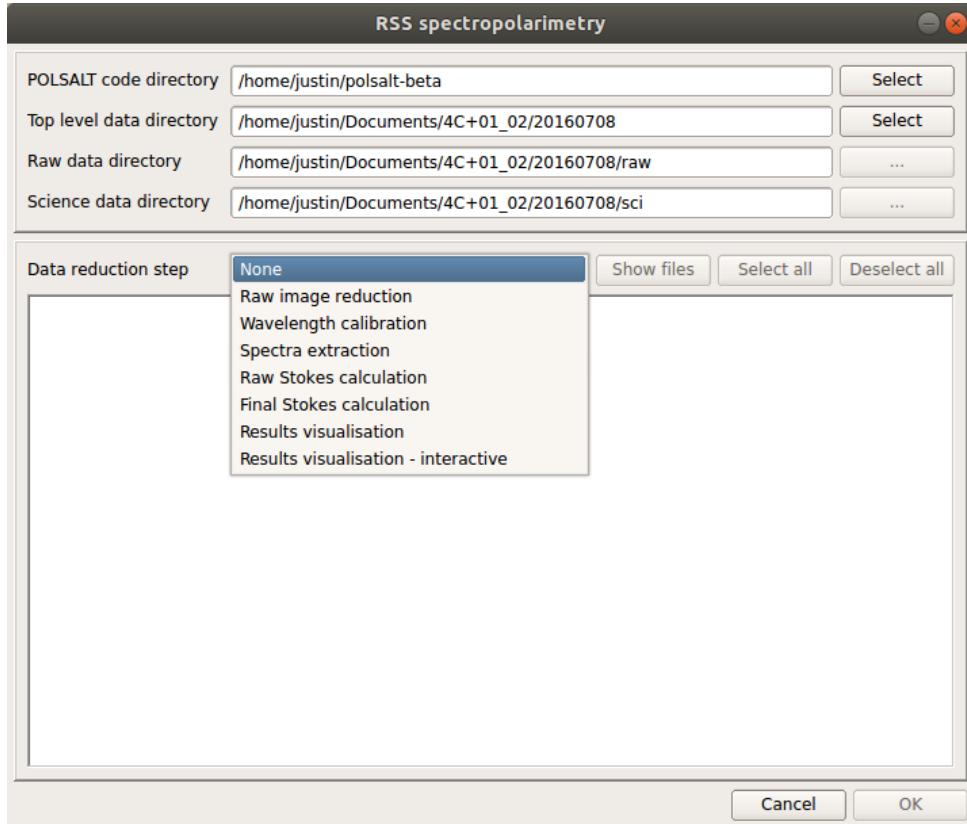


Figure 3.1: The layout of the `POLSALT` Graphical User Interface (GUI), including the contents of the reduction steps accessible via the dropdown box. Note that there is no trailing forward slash after the ‘Top level data directory’. Figure created from local instance of the `POLSALT` GUI.

the bad pixel maps and pixel variance information. Files with basic reductions performed have “`mxgbp`” prepended to their names. As of February 2022, basic CCD reductions are automatically run for all RSS spectropolarimetric observations as part of the default SALT basic reduction pipeline that is run daily.

3.1.2 Wavelength calibrations

Wavelength calibration and cosmic-ray rejection is performed via `specpolwavmap.py` and separately calibrates the *O*- and *E*-beams, based on the arc frames, and applies a simple cosmic-ray rejection for all science frames. This step is interactive and allows the user to individually fit wavelength calibration maps to each beam. The importance of an accurate correlation between both beams has been touched on previously (§ 2.3.2) and will be further discussed in § 3.1.8. The wavelength calibrated results are saved as an additional extension to each science FITS file, which are prefixed with a “`w`”, and the *O*- and *E*-beams of the extensions are split into their own sub-extensions.

3.1.3 Spectral extraction

Background subtraction and spectral extraction is run via `specpoleextract_dev.py` which corrects for the beam-splitter distortion and tilt, performs sky subtraction, and extracts a one dimensional wavelength dependent spectrum for each beam sub-extension. This step is interactive and, using the brightest trace in the images, allows the user to define regions which span the wavelength axis and which define the background and trace

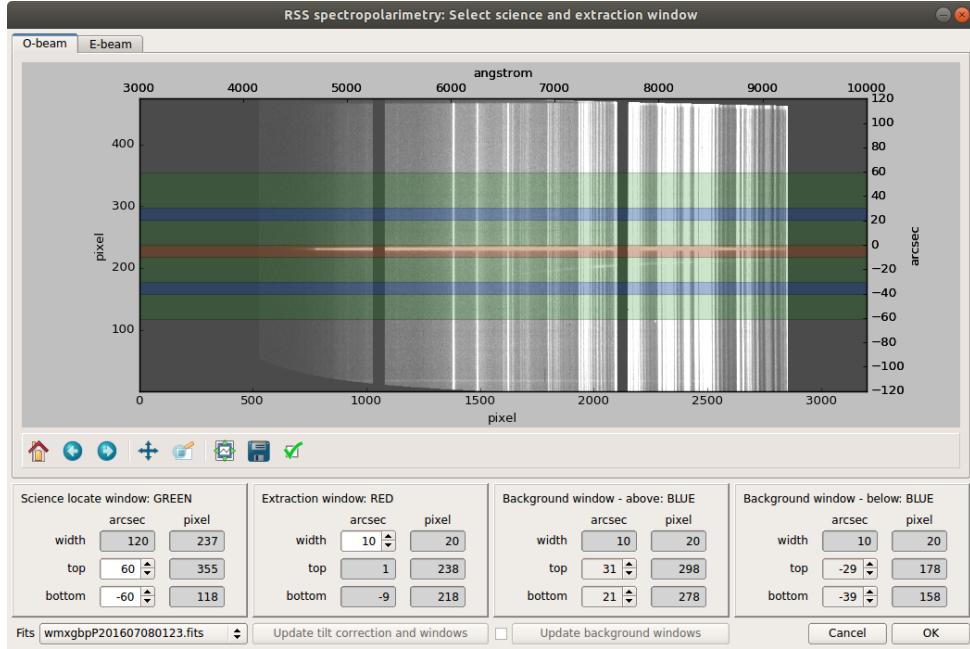


Figure 3.2: The layout of the interactive POLSALT spectra extraction GUI after selecting the ‘update tilt correction and windows’ button along the bottom border of the window. Figure created from local instance of the POLSALT GUI.

regions for the sky subtraction and spectral extraction. Files with corrections applied are saved with “c” prepended to their names and files which contain the extracted one dimensional spectrum have “e” further prepended to their names.

3.1.4 Raw Stokes calculations

Raw Stokes calculations are performed via `specpolrawstokes_dev.py` and identify waveplate pairs for which the intensity, I , and a ‘raw Stokes’ signal, S , are calculated as:

$$I = \frac{1}{2}(O_1 + O_2 + E_1 + E_2), \text{ and} \quad (3.1)$$

$$S = \frac{1}{2} \left[\left(\frac{O_1 - O_2}{O_1 + O_2} \right) - \left(\frac{E_1 - E_2}{E_1 + E_2} \right) \right]. \quad (3.2)$$

The raw Stokes signal is calculated as the normalized difference of the O - and E -beams, for a waveplate pair, taken perpendicular to one another. The files generated containing the raw Stokes information have a very specific naming style, with most notably the pair of frames being used included in the file names.

3.1.5 Final Stokes calculations

The Final Stokes calculations are performed via `specpolfinalstokes.py` and, using the waveplate pattern along with the raw Stokes signals, calibrate for polarimetric zero-point and waveplate efficiency calibrations and calculates the final Stokes parameters. Before the final Stokes calculations are performed, data culling is applied to the raw Stokes to eliminate outlier results which may arise due to, for example, atmospheric conditions. Data culling compares observation cycles against one another, compares the deviation of the means which estimate the systematic polarization baseline fluctuations (due to imperfections in repeatability), and performs a chi-squared analysis to eliminate outliers.

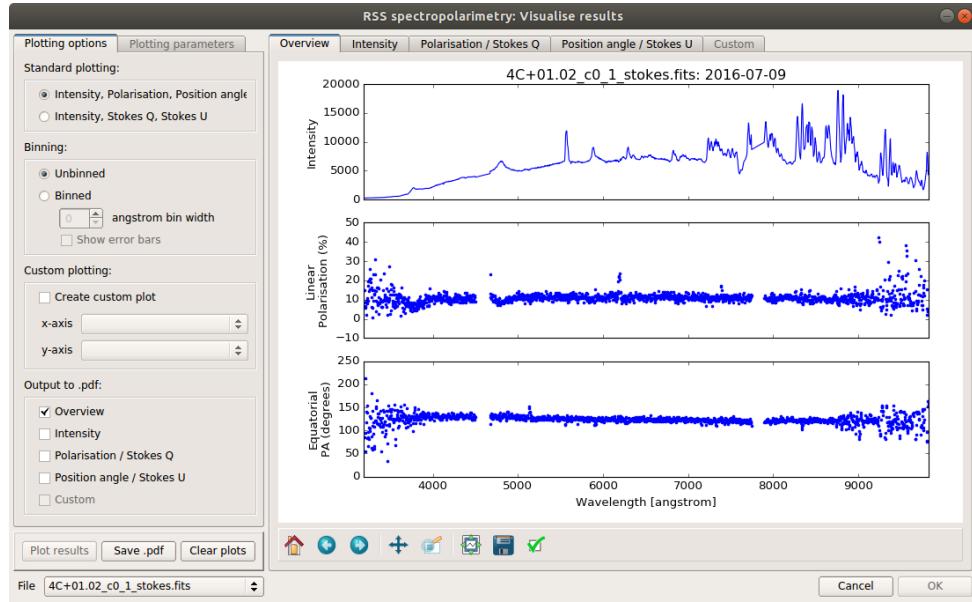


Figure 3.3: The layout of the interactive POLSALT visualization GUI after selecting the ‘Plot results’ button along the bottom border of the window. Figure created from local instance of the POLSALT GUI.

3.1.6 Visualization

Plotting the results of the spectropolarimetric reduction process uses **specpolview.py** and generates a plot of the Intensity, Linear Polarization (%), and Equatorial Polarization Angle ($^{\circ}$) against a shared wavelength axis, as seen in Figure 3.4. This step is interactive and various options, such as the wavelength range, binning, etc., are available.

3.1.7 Post-processing analysis

Generally, the plot of the spectropolarimetric results is the stopping point for most reduction procedures as it contains or creates the desired results. However, additional tools exist which may be used after the polarization reductions, and which are not represented in the GUI, namely, flux calibration and synthetic filtering.

Flux-calibrations are performed via **specpolflux.py** and are only intended for shape corrections of the spectrum. Additionally, the flux database file must exist for the standard observed and must be copied over to the working science directory.

Synthetic filtering is calculated via **specpolfilter.py** and computes the synthetically filtered polarization results. The filters which can be synthesized are the Johnson *U*, *B*, and *V* filter curves from the SALTICAM filters, as well as the Cousins *R* and *I* filter curves, along with any user defined wavelength dependent throughput filter curves.

3.1.8 Limitations of POLSALT and the Need for Supplementary Tools

The creation of supplementary tools for POLSALT spectropolarimetric reductions stemmed from the limitations of the wavelength calibration process and a need for a way to compare wavelength solutions across matching *O* and *E* polarization beams. The process of calibrating wavelength solutions using the POLSALT pipeline is time-consuming for the

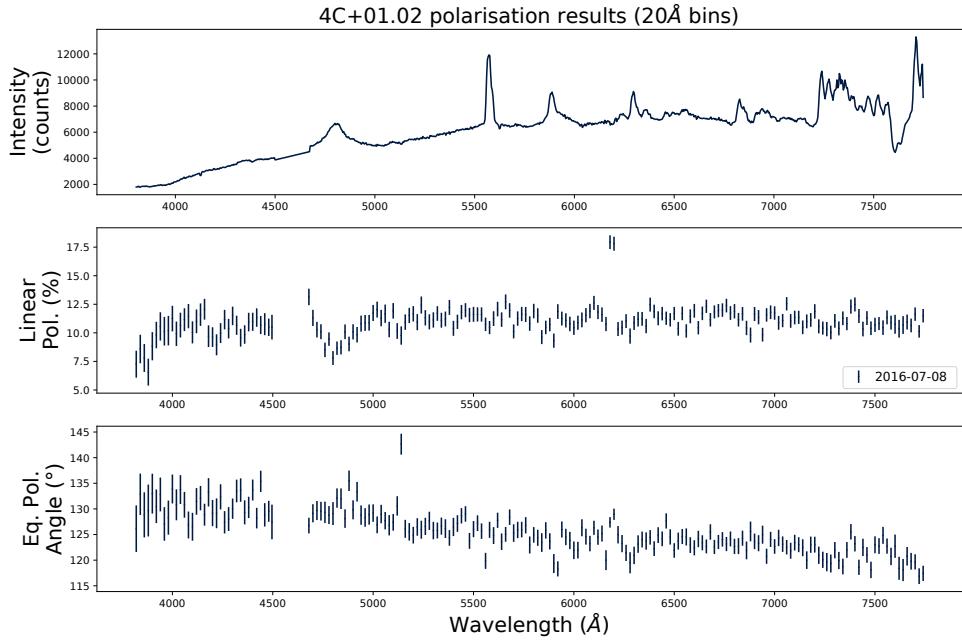


Figure 3.4: A typical plot resulting from the reduction process. Figure adapted from (Cooper et al., 2022).

average user, and often results in unexpected crashes when receiving erroneous inputs or key presses. Due to the time-consuming process of recalibrating the wavelength solutions it is not feasible to perform the wavelength calibrations time and time again for any amount of reductions larger than a handful of observations.

The prime motivation of finding an alternate method to wavelength calibrate SALT spectropolarimetric data stemmed from a large backlog of unused data taken using the PG0300. The only arc available for the PG0300 with a close enough articulation and grating angle ($\sim 10.68^\circ$ and $\sim 5.38^\circ$, respectively) was SALT's Argon lamp which displayed sparse spectral features with large gaps over the wavelength range at these grating and articulation angles (Figure 3.5). This often lead the POLSALT pipeline to create inconsistent wavelength solutions, or fail to create a wavelength solution altogether, since minor deviations of identified spectral features result in large deviations in regions with no spectral features. To only further compound the difficulty of the wavelength calibrations, the spectrum of the Ar arc lamp contains a partial overlap of a differing order at higher wavelengths and is thus not a purely free spectral range (§ 2.1.7, Equation 2.5).

The chosen solution was to use a well established tool to perform the wavelength calibration - one which allows for rapid recalibrations as well as provides a familiar interface with which the user can analyze their wavelength solutions. IRAF provides this familiar environment and reliability, even when considering its age and limited community development.

Unfortunately, IRAF is unable to natively parse the file structure implemented by POLSALT ‘as is’ and formatting of the data structures are necessary for integration purposes. This restructuring works both ways as once the IRAF reductions are complete the format must be reformatted to match that of the POLSALT `wavelength calibration` output such that the reduction process may be completed in POLSALT.

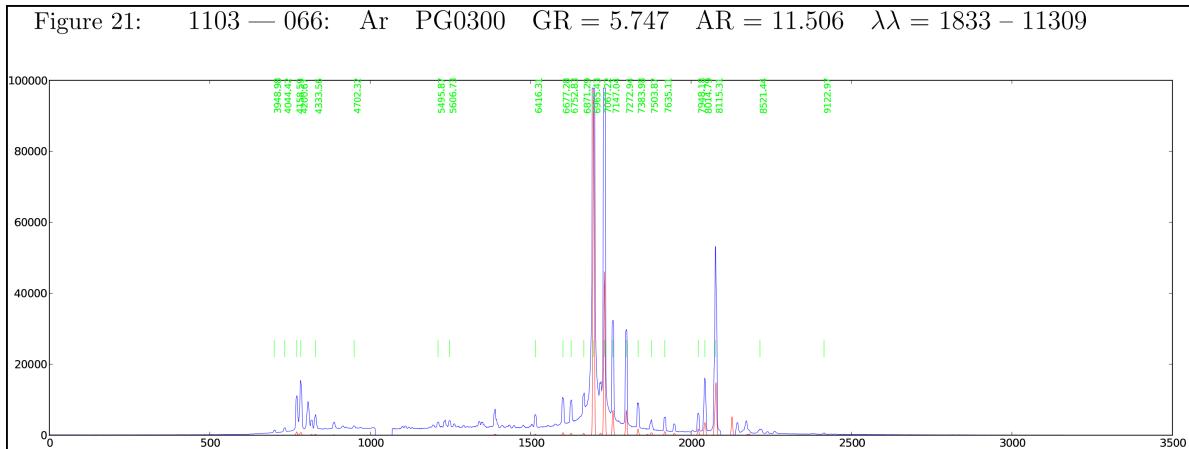


Figure 3.5: One of many Argon arc lamp spectra as provided by SALT for line identification. Plot adapted from SALT’s published Longslit Line Atlases (as of 2024), resized to fit within the document margins but otherwise unchanged.⁴

Another option to perform the wavelength calibration is Python which allows for a more modern and flexible approach, but is not discussed here. What will be discussed, however, is the structure of the wavelength solutions created through Python to be later reintroduced to the POLSALT pipeline. The solutions must be stored such that the ‘*x*’ and ‘*y*’ orders of the solution, as well as all the coefficients (C_{00} to C_{xy}) making up the solution, separated by new lines, are included. The only limitations to the names of the solution files is that they must make mention of the specific *O*- or *E*-beam as well as the wavelength solution type (e.g. ‘Chebyshev’, ‘Legendre’, etc.).

3.2 IRAF - Image Reduction and Analysis Facility

IRAF is a collection of software designed specifically for the reduction and analysis of astronomical images and spectra. The software consists of many tasks which perform specific operations and which are grouped into relevant packages. Only a brief overview of the tasks will be provided here as every institute and individual has their own preferred wavelength calibration procedures and often use specific parameters for the various IRAF tasks (e.g. the order and type of the polynomial used in `identify`, etc.).

A useful IRAF task that will not be discussed but nevertheless deserves a mention is the `mkscript` task in the `system` package which allows a user to create and save a task along with the defined parameters as a file which can later be called as a script. It is instrumental as a scripting aid and is what allows IRAF its rapid recalibrations of the wavelength solutions.

Help documentation for any of the IRAF tasks may be found online under <https://iraf.net/irafdocs/> or through the IRAF Command Line Interface (CLI) through the `? or ::help 'cursor commands'` when running interactive tasks.

For wavelength calibrations of spectropolarimetric observations taken with the SALT RSS, the relevant tasks, in order, are the `identify` and `reidentify` tasks located in the

⁴‘low resolution’ Ar plot sourced from <https://astronomers.salt.ac.za/data/salt-longslit-line-atlas/>

`noao.onedspec` package, and the `fitcoords` and optionally the `transform` tasks located under the `noao.twodspec.longslit` package. These tasks produce a two-dimensional wavelength solution and must each be run twice to find the wavelength solutions for both spectropolarimetric beams.

3.2.1 Identify

The `identify` task is used to interactively determine a one-dimensional wavelength function across a chosen row of an arc exposure by identifying features in the spectrum with known wavelengths.⁵ The task creates the first approximation of the wavelength solution as well as a local database in which the solution is saved.⁶ Both solution and database are built on in subsequent tasks, and it is therefore imperative that the initial solution is well-fit to minimize errors further down the calibration process.

The process of using `identify` consists of identifying known features spanning the entire wavelength range and then removing identified features which negatively impact the wavelength solution. A balance must be found between the number of identified features and parameters of the fit against the deviation of the fit from the known features.

3.2.2 Reidentify

The `reidentify` task is used to run the `identify` task autonomously and repeatedly across the entirety of the arc exposure at a defined interval.⁷ The task uses the one-dimensional wavelength solution stored in the database created by the initial `identify` call and refits the previously identified points to match the new positions of the relevant spectral features. The task may fail based on a number of defined conditions, most common of which is the loss of features as the task moves further from the row at which the user ran `identify`.

When running `reidentify` non-interactively, it is recommended to set the `verbose` parameter to ‘yes’ as this will provide immediate confirmation of whether the task quit early or not. Regardless of whether the task quit successfully or not, the newly defined wavelength solutions are appended to the local database following the `identify` task database format.

3.2.3 Fitcoords

The `fitcoords` task is used to combine the collection of one-dimensional wavelength solutions in the local database to a two-dimensional surface function.⁸ This surface function is the final two-dimensional wavelength solution and is what is needed to convert the IRAF formatted wavelength calibrated Flexible Image Transport System (FITS) files back into

⁵Help documentation for the `identify` task may be found at https://astro.uni-bonn.de/~sysstw/lfa_html/iraf/noao.onedspec.identify.html.

⁶The structure of the `identify` database entry may be found at <https://iraf.net/irafdocs/formats/identify.php>.

⁷Help documentation for the `reidentify` task may be found at https://astro.uni-bonn.de/~sysstw/lfa_html/iraf/noao.onedspec.reidentify.html.

⁸Help documentation for the `fitcoords` task may be found at https://astro.uni-bonn.de/~sysstw/lfa_html/iraf/noao.twodspec.longslit.fitcoords.html.

TODO: Include poor, dubious, and well transformed image examples

Figure 3.6: Examples of a terrible-, poorly-, and well-fit wavelength solution. Figures created by the `IRAF transform` task.

the POLSALT format. The solution is stored in the local IRAF database and is the solution used by the STOPS `join` method.⁹

The process of using `fitcoords`, follows closely to that of `identify` and consists of examining the distribution of identified points and eliminating any points that `reidentify` may have misidentified. By eliminating outliers with bad residuals and modifying the two-dimensional surface function's type and degree, the overall error of the fit decreases, aligning more closely to what the ‘true’ wavelength solution is.

3.2.4 Transform

The `transform` task is the optional final step in the IRAF wavelength calibration process and is quick to run and easy to script.¹⁰ The task converts the (pixel, pixel) units of an exposure to (wavelength, pixel) units which allows for an immediate check whether the wavelength solution is consistent across the frame. Any general error in the wavelength solution may be spotted in the transformed images; ranging from minor errors, such as the arc exposure’s arc lines or science exposure’s sky lines not being straight across the columns of the frame, to more major errors, such as an incorrect wavelength solution skewing the exposure beyond recognition.

3.3 STOPS - Supplementary Tools for POLSALT Spectro-polarimetry

STOPS allows an alternate method for wavelength calibrations, namely IRAF, to be used instead of POLSALT’s wavelength calibration. The parsing of POLSALT data into an IRAF usable format and the reformatting of the IRAF wavelength calibrated data back into a POLSALT usable format, referred to as *splitting* and *joining*, is performed by the STOPS `split` and `join` methods, respectively.

Methods to verify the validity of the alternate wavelength calibrations were also added to STOPS. The first of these methods checks the sky line wavelength (*x*) positions across the frame as well as the variation of the sky lines across the positional (*y*) axis of the frame, named `skyline`. The second of these methods checks the correlation of the *O*- and *E*-beams either within a given FITS file or across multiple files (comparing only the *O*- and *E*-beams for each), named `correlate`. With these two additional methods, a user is able to verify that the wavelength solutions do not conflict across the *O*- and *E*-beams and that no unexpected deviations are included in the wavelength solutions.

Help for the STOPS CLI commands may be found either by running:

⁹The structure of the `fitcoords` database entry may be found at <https://iraf.net/irafdocs/formats/fitcoords.php>.

¹⁰Help documentation for the `transform` task may be found at https://astro.uni-bonn.de/~sysstw/lfa_html/iraf/noao.twodspec.longslit.transform.html.

```
$ python ~/STOPS --help
```

or in Listing II.1. Help for the STOPS specific mode commands may be found by running:

```
$ python ~/STOPS [split|join|correlate|skylines] --help
```

Finally, help documentation for the STOPS methods may be found within this section (Listing 3.1 to 3.4) or in Appendix II.

3.3.1 Splitting

Listing 3.1: The ‘docstring’ for `split.py`

```

26 """
27 The `Split` class allows for the splitting of `polsalt` FITS files
28 based on the polarization beam. The FITS files must have basic
29 `polsalt` pre-reductions already applied (`mxbp...` FITS files).
30
31 Parameters
32 -----
33 data_dir : str
34     The path to the data to be split
35 fits_list : list[str], optional
36     A list of pre-reduced `polsalt` FITS files to be split within `data_dir`.
37     (The default is None, `Split` will search for `mxbp*.fits` files)
38 split_row : int, optional
39     The row along which to split the data of each extension in the FITS file.
40     (The default is SPLIT_ROW (See Notes), the SALT RSS CCD's middle row)
41 no_arc : bool, optional
42     Decides whether the arc frames should be recombined.
43     (The default is False, `polsalt` has no use for the arc after wavelength
44     ↪ calibrations)
45 save_prefix : dict[str, list[str]], optional
46     The prefix with which to save the O & E beams.
47     Setting `save_prefix` = ``None`` does not save the split O & E beams.
48     (The default is SAVE_PREFIX (See Notes))
49
50 Attributes
51 -----
52 arc : str
53     Name of arc FITS file within `data_dir`.
54     `arc` = `""` if `no_arc` or not detected in `data_dir`.
55 o_files, e_files : list[str]
56     A list of the `O`- and `E`-beam FITS file names.
57     The first entry is the arc file if `arc` defined.
58 data_dir
59 fits_list
60 split_row
61 save_prefix
62
63 Methods
64 -----
65 split_file(file: os.PathLike)
66     -> tuple[astropy.io.fits.HDUList]
67     Handles creation and saving the separated FITS files
68 split_ext(hdulist: astropy.io.fits.HDUList, ext: str = 'SCI')
69     -> astropy.io.fits.HDUList
70     Splits the data in the `ext` extension along the `split_row`
71 crop_file(hdulist: astropy.io.fits.HDUList, crop: int = CROP_DEFAULT (See Notes))
72     -> tuple[numumpy.ndarray]
73     Crops the data along the edge of the frame, that is,
74     `O`-beam cropped as [crop:], and
75     `E`-beam cropped as [: - crop].
76 update_beam_lists(o_name: str, e_name: str)
77     -> None
78     Updates `o_files` and `e_files`.
79 save_beam_lists(file_suffix: str = 'frames')
80     -> None

```

```

81     Creates (Overwrites if exists) and writes the `o_files` and `e_files` to files named
82     `o_{file_suffix}` and `e_{file_suffix}`, respectively.
83     process()
84     -> None
85     Calls `split_file` and `save_beam_lists` on each file in `fits_list` for automation.
86
87 Other Parameters
88 -----
89 **kwargs : dict
90     keyword arguments. Allows for passing unpacked dictionary to the class constructor.
91
92 Notes
93 -----
94 Constants Imported (See utils.Constants):
95     SAVE_PREFIX
96     CROP_DEFAULT
97     SPLIT_ROW
98
99 """

```

As mentioned previously, the format of the FITS file created by POLSALT after basic CCD reductions and the format expected by IRAF to be used for the wavelength calibrations are incompatible. Basic POLSALT CCD reductions return FITS files which contain a primary header along with extensions for the science, variance, and Bad Pixel Map (BPM) images. These extensions carry the image of the trace for both polarimetry beams (see Figure 3.13), the variance of the image, and a map of the pixels to be masked out, respectively.

IRAF is capable of dealing with multiple traces in an extension or lists of input files but is not as capable when dealing with multiple wavelength solutions contained in a single extension (as expected by the POLSALT `wavelength calibration`) or extensions containing sub-extensions (as expected by the POLSALT `spectral extraction`). To simplify the IRAF reduction procedure it was decided to separate the perpendicular polarization beams into their own files.

The files with POLSALT pre-reductions applied, namely FITS files with an ‘mxgbp’ prefix (§ 3.1), are used as the starting point for the supplementary tool’s `split` method. Running `split` finds all the FITS files for wavelength calibration within the working directory, creates two empty Header Data Unit (HDU) structures for each sub-extension of the FITS file, and appends all science and header data necessary for wavelength calibration to the relevant HDU structure.

As the intent was always to parse the wavelength function back into POLSALT it was decided to keep these temporary FITS files as small as possible. This is especially necessary when considering the amount of exposures that are taken for a single spectropolarimetric observation run, and then how the number of observations increases for long term studies.

To aid the scripting of the IRAF wavelength calibration process, the `split` method also performs row cropping to exclude CCD regions with no exposure and creates files listing the split *O*- and *E*-beam FITS files to simplify the IRAF task inputs.¹¹ Otherwise,

¹¹Row cropping was decided on as IRAF does not handle rows with no exposure well, specifically when it comes to the `reidentify` task.

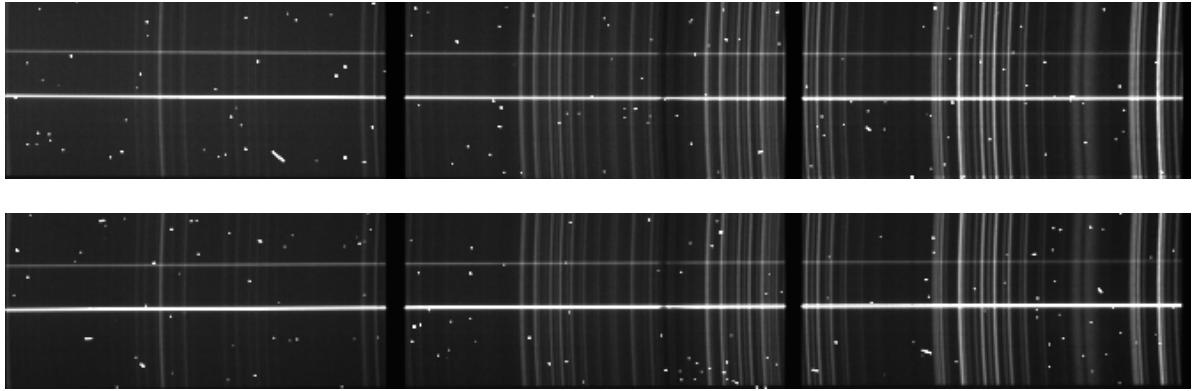


Figure 3.7: The split *O*- and *E*-beams as handed to IRAF. Figure created from the STOPS `split` method output.

defaults, such as which row to split the beams along, were kept as close to the POLSALT pipeline as possible.

3.3.2 Joining

Listing 3.2: The ‘docstring’ for `join.py`

```

32
33     """
34     The `Join` class allows for the joining of previously
35     split files and the appending of an external wavelength
36     solution to the `polsalt` FITS file format.
37
38     Parameters
39     -----
40     data_dir : str
41         The path to the data to be joined
42     database : str, optional
43         The name of the `IRAF` database folder.
44         (The default is "database")
45     fits_list : list[str], optional
46         A list of pre-reduced `polsalt` FITS files to be joined within `data_dir`.
47         (The default is ``None``, `Join` will search for `mxgbp*.fits` files)
48     solutions_list: list[str], optional
49         A list of solution filenames from which the wavelength solution is created.
50         (The default is ``None``, `Join` will search for `fc*` files within the `database`
51         ↪ directory)
52     split_row : int, optional
53         The row along which the data of each extension in the FITS file was split.
54         Necessary when Joining cropped files.
55         (The default is 517, the SALT RSS CCD's middle row)
56     save_prefix : dict[str, list[str]], optional
57         The prefix with which the previously split `O`- & `E`-beams were saved.
58         Used for detecting if cropping was applied during the splitting procedure.
59         (The default is SAVE_PREFIX (See Notes))
60     verbose : int, optional
61         The level of verbosity to use for the Cosmic ray rejection
62         (The default is 30, I.E. logging.INFO)
63
64     Attributes
65     -----
66     fc_files : list[str]
67         Valid solutions found from `solutions_list`.
68     custom : bool
69         Internal flag for whether `solutions_list` uses the `IRAF` or a custom format.
70         See Notes for custom solution formatting.
71         (Default (inherited from `solutions_list`) is False)
72     arc : str
73         Deprecated. Name of arc FITS file within `data_dir`.
    
```

```

74 database
75 fits_list
76 split_row
77 save_prefix
78
79
80 Methods
81 -----
82 get_solutions(wavlist: list / None, prefix: str = "fc")
83     -> (fc_files, custom): tuple[list[str], bool]
84     Parse `solutions_list` and return valid solution files and if they are non-`IRAF`
85     ↪ solutions.
86 parse_solution(fc_file: str, xshape: int, yshape: int)
87     -> tuple[dict[str, int], np.ndarray]
88     Loads the wavelength solution file and parses keywords necessary for creating the
89     ↪ wavelength extension.
90 join_file(file: os.PathLike)
91     -> None
92     Joins the files,
93     attaches the wavelength solutions,
94     performs cosmic ray cleaning,
95     masks the extension,
96     and checks cropping performed in `Split`.
97     Writes the FITS file in a `polsalt` valid format.
98 check_crop(hdu: pyfits.HDUList, o_file: str, e_file: str)
99     -> int
100    Opens the split `O`- and `E`-beam FITS files and returns the amount of cropping
101    ↪ that was performed.
102 process()
103     -> None
104     Calls `join_file` on each file in `fits_list` for automation.
105
106 Other Parameters
107 -----
108 no_arc : bool, optional
109     Deprecated. Decides whether the arc frames should be processed.
110     (The default is False, `polsalt` has no use for the arc after wavelength
111     ↪ calibrations)
112 **kwargs : dict
113     keyword arguments. Allows for passing unpacked dictionary to the class constructor.
114
115 Notes
116 -----
117 Constants Imported (See utils.Constants):
118     DATADIR
119     SAVE_PREFIX
120     SPLIT_ROW
121     CR_PARAMS
122
123 Custom wavelength solutions must be formatted as:
124     `x`,
125     `y`,
126     *coefficients...
127 where the solutions are of order (`x` by `y`) and contain xy coefficients.
128 The name of the custom wavelength solution file must contain either "cheb" or "leg"
129 for Chebychev or Legendre wavelength solutions, respectively.
130
131 References
132 -----
133 .. [1] van Dokkum 2001, PASP, 113, 789, 1420 (article :
134     ↪ http://adsabs.harvard.edu/abs/2001PASP..113.1420V)
135 .. [2] https://zenodo.org/records/1482019
136
137 """

```

As mentioned previously, the format of the FITS file created by IRAF after wavelength calibrations and that expected by POLSALT for the spectra extraction are incompatible.

ble. A typical FITS file expected by the POLSALT `spectra extraction` contains a primary header along with the various image extensions, the most notable extension being the newly created wavelength extension. All images contained within the extensions have the trace for both polarimetry beams split, as seen in Figure 3.9 and the headers of each extension updated.

All pieces necessary to recreate the POLSALT wavelength calibrated FITS files exist once the `IRAF` procedure to generate the database entry for the two-dimensional wavelength solution is complete. The `join` method of the supplementary tools is used at this point and, once run, automatically creates the desired files.

Running `join` finds all the relevant FITS and local database files necessary to run the POLSALT `spectra extraction`, creates an empty HDU structure for each pair of matching spectropolarimetric beams, copies over the extensions and their respective image and header information, checks and corrects the trace splitting to best match that of POLSALT, appends a new extension and parses the database wavelength solutions into the POLSALT intensity-wavelength format, cleans the science extension for cosmic rays, and does some house-cleaning to align the finalized FITS files to those created when using the ‘pure’ POLSALT pipeline.

The wavelength database file, described in § 3.2.3, is parsed by `join` which creates a function that provides the corresponding wavelength when provided with a (*pixel, pixel*) position. This is used to fill the pixels of the wavelength extension with their respective wavelength, as seen in Figure 3.8. Note that regions which fall outside the exposed region are masked by setting the corresponding pixel values of the wavelength and BPM extensions to 0.

The FITS files created by the `join` method and POLSALT pipeline’s `wavelength calibration` method are almost identical. The only difference between the FITS files is the shape of the images stored within them, reflected also through specifically the ‘NAXIS2’ header keyword, since `split` introduces a cropping. It was deemed unnecessary to reintroduce the cropped region as it is promptly discarded in the following POLSALT `spectra extraction` process and raises no issues when left out. Otherwise, both the `join` method and POLSALT `wavelength calibration` update the headers to reflect the new shape of the data and data type, through header keywords ‘CTYPE3’ and ‘BITPIX’, respectively.

The `join` method cleans the science extension of cosmic rays using the `lacosmic` python package which was specifically designed for this purpose and uses the L.A. Cosmic algorithm, based on Laplacian edge detection. The read noise and gain parameters used for cosmic ray cleaning were chosen based on the properties of the RSS, while the rest were chosen following the publication and suggestions¹² by the algorithm’s creator, as well as the implementation of the algorithm in the python `ccdproc` package (McCully et al., 2018; van Dokkum, 2001). The chosen parameters work well for most cosmic rays, as can be seen when comparing Figure 3.7 to Figure 3.9, but may be modified as needed.

¹²Suggested parameters for the `lacosmic` algorithm may be found at <http://www.astro.yale.edu/dokkum/lacosmic/pars.html>.

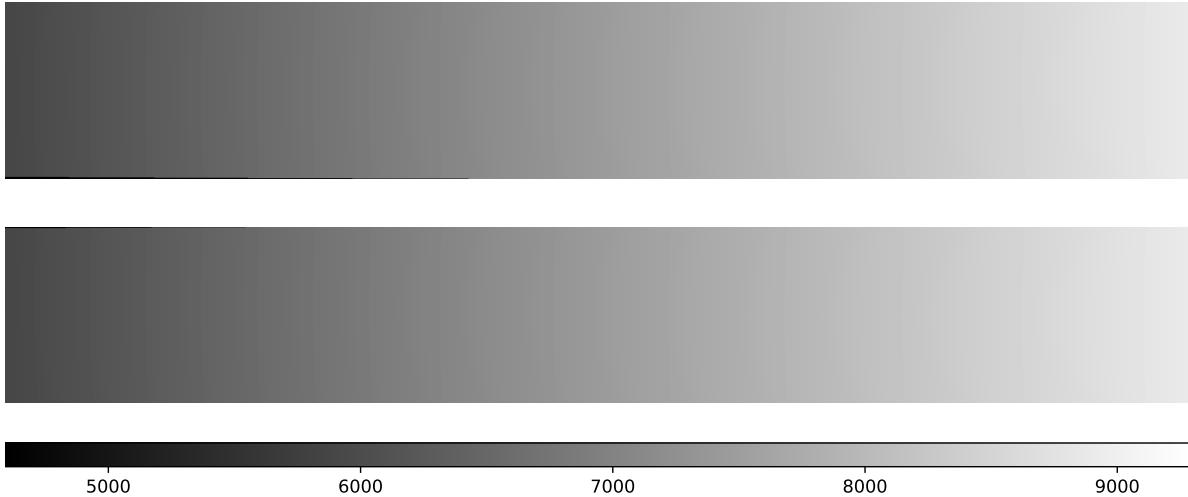


Figure 3.8: The wavelength extension of a FITS file ready to be handed back to the `POLSLT` pipeline. The color bar displays the wavelength in Å as displayed by the *O*- and *E*-beam sub-extensions. Figure created from the `STOPs join` method output.

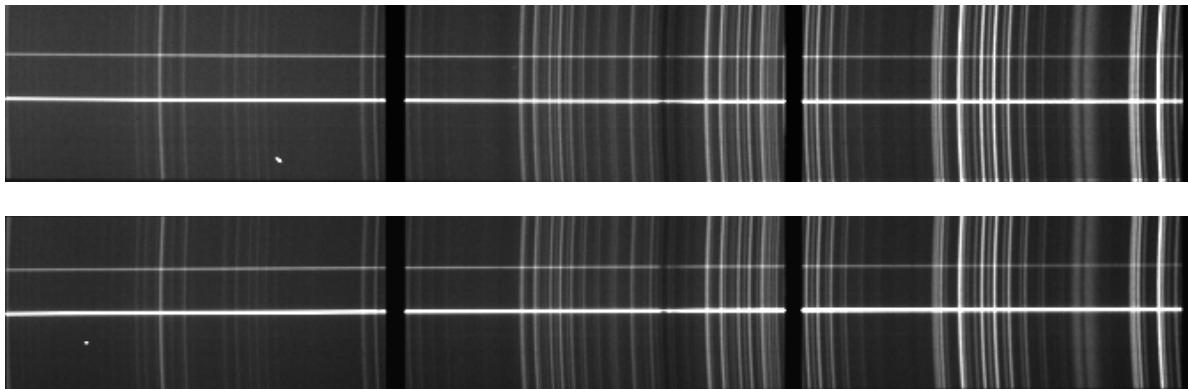


Figure 3.9: A representative science extension of a FITS file capable of being parsed by the `POLSLT` pipeline. The intensity of the *O*- and *E*-beam sub-extensions are displayed via the grayscale value at each pixel. Note the inclusion of regions of: solid black demarcating the chip gaps, horizontal stripes of high intensity demarcating the trace, and (curved) vertical stripes of high intensity demarcating the sky lines. Figure created from the `STOPs STOPsjoin` method output.

The wavelength extension is masked to remove any wavelength regions not calibrated for by SALT as well as masked for the skewing of the trace introduced by the wollaston element. The masking of the wollaston skewing is necessary since `POLSLT` introduces a wollaston correction in the `spectra extraction` process. Finally, the BPM extension is masked to reflect the valid wavelength calibrated regions for both spectropolarimetric beams and the files are saved with the `POLSLT` wavelength calibrated ‘wmxgbp’ prefix.

3.3.3 Sky line checks

Listing 3.3: The ‘docstring’ for `skylines.py`

```

30
31 """
32 Class representing the Skyline object.
33
34 Parameters
35 -----
36 data_dir : Path
37     The directory containing the data files.
38 filenames : list[str]

```

TODO: Include example of skyline result

Figure 3.10: The resultant output plot of the STOPS `skylines` method. Figure created via the STOPS `skyline` method.

```

39     The list of filenames to be processed.
40     beam : str, optional
41         The beam mode, by default "OE".
42     plot : bool, optional
43         Flag indicating whether to plot the continuum, by default False.
44     save_prefix : Path / None, optional
45         The prefix for saving the data, by default None.
46     **kwargs
47         Additional keyword arguments.
48
49     Attributes
50     -----
51     data_dir : Path
52         The directory containing the data files.
53     fits_list : list[str]
54         The list of fits file paths.
55     beam : str
56         The beam mode.
57     can_plot : bool
58         Flag indicating whether to plot the continuum.
59     save_prefix : Path / None
60         The prefix for saving the data.
61     wav_unit : str
62         The unit of wavelength.
63     rawWav : np.ndarray
64         The raw wavelength data.
65     rawSpec : np.ndarray
66         The raw spectral data.
67     rawBpm : np.ndarray
68         The raw bad pixel mask data.
69     corrWav : np.ndarray
70         The corrected wavelength data.
71     corrSpec : np.ndarray
72         The corrected spectral data.
73     spec : np.ndarray
74         The median spectrum.
75     normSpec : np.ndarray
76         The normalized spectrum.
77
78     Methods
79     -----
80     checkLoad(self, path1: str) -> np.ndarray:
81         Checks and loads the data from the given path.
82     transform(self, wav_sol: np.ndarray, spec: np.ndarray) -> np.ndarray:
83         Transforms the input wavelength and spectral data based on the given wavelength
84         ↪ solution.
84     rmvCont(self) -> np.ndarray:
85         Removes the continuum from the spectrum.
86     skylines(self) -> None:
87         Placeholder method for processing skylines.
88     process(self) -> None:
89         Placeholder method for processing the data.
90     """

```

Sky line comparisons serve two unique yet interconnected functions. Firstly, they naively transform the wavelength calibrated frames, without conserving flux, allowing the user to confirm the variation of sky lines across the columns of the frame, and secondly, they compare the observed wavelength positions of the sky lines with the calibrated wavelength positions of the SALT sky lines,¹³ allowing confirmation of the wavelength solution at positions across the rows of the frame. The file used for skyline comparisons may either

¹³The first iteration of a sky line atlas is available at <https://astronomers.salt.ac.za/data/salt-longslit-line-atlas/>

be the IRAF `transform` FITS file, which allows for flux conservation through the ‘`flux`’ parameter, or the ‘`wmxgbp`’ files created by `join`.

The `skyline` method loads the wavelength calibrated files, transforms the frames if the frame was not transformed by IRAF’s `transform` method, removes the continuum, compares the cross-column sky lines to those of a single row, and compares the wavelength position of said sky lines to the reference sky lines as measured by SALT.

Determining if there is any inaccuracy in the wavelength solution in the spatial (y , or vertical) axis is relatively straightforward as a perfect wavelength solution will remove any horizontal variation of the sky lines. Any horizontal deviation of the sky lines after transformation reflects a poor fit of the wavelength solution. Any vertical variation may be found through a quick visual inspection of a transformed frame, as mentioned in § 3.2.4, but may be inspected more thoroughly using the `skyline` method. As mentioned, the sky lines are averaged and compared to sky lines of a typical row. A wavelength solution exhibiting a poor fit across the spatial axis will display broader averaged sky lines than those of a relatively good fit.

As no features, other than the trace of sources exposed across a frame, exist that uniformly cover the wavelength (x , horizontal) axis of a typical frame, determining if the horizontal fit of the wavelength solution is more challenging. Thankfully, SALT has published a sky line atlas which we may make use of. By first considering the spatial fit of the wavelength solution, it is ensured that the wavelength positions of all sky lines are well-defined. Comparisons may now be made to the wavelength positions measured by SALT. Minor variations in the comparison of the sky lines are expected, but any uniform trends indicate an underlying poor fit across the wavelength axis of the wavelength solution. A poor horizontal fit is difficult to spot without supplementary tools and may have drastic adverse effect on the final polarization results.

3.3.4 Cross correlation

Listing 3.4: The ‘docstring’ for `cross_correlate.py`

```

34
35      """
36      Cross correlate allows for comparing the extensions of multiple
37      FITS files, or comparing the D and E beams of a single FITS file.
38
39      Parameters
40      -----
41      data_dir : str
42          The path to the data to be cross correlated
43      filenames : list[str]
44          The ecwmxgbp*.fits files to be cross correlated.
45          If only one filename is defined, correlation is done against the two polarization
46          ↪ beams.
47      split_ccd : bool, optional
48          Decides whether the CCD regions should each be individually cross correlated.
49          (The default is True, which splits the spectrum up into its separate CCD regions)
50      cont_ord : int, optional
51          The degree of a chebyshev to fit to the continuum.
52          (The default is 11)
53      plot : bool, optional
54          Decides whether or not the continuum fitting should be plotted
55          (The default is False, so no continua plots are displayed)
56      save_prefix : str, optional
57          The name or directory to save the figure produced to.

```

```

57     """ saves a default name to the current working. A default name is also used when
58     ↪ save_prefix is a directory.
59     (The default is None, I.E. The figure is not saved, only displayed)
60
61 Attributes
62 -----
63 data_dir
64 fits_list
65 beams : str
66     The mode of correlation.
67     'DE' for same file, and 'D' or 'E' for different files but same ext's.
68 ccds : int
69     The number of CCD's in the data. Used to split the CCD's if split_ccd is True.
70 cont_ord : int
71     The degree of the chebyshev to fit to the continuum.
72 can_plot : bool
73     Decides whether or not the continuum fitting should be plotted
74 offset : int
75     The amount the spectrum is shifted, mainly to test the effect of the cross
76     ↪ correlation
77     (The default is 0, I.E. no offset introduced)
78 save_prefix
79 wav_unit : str
80     The units of the wavelength axis.
81     (The default is Angstroms)
82 wav_cdelt : int
83     The wavelength increment.
84     (The default is 1)
85 alt : Callable
86     An alternate method of cross correlating the data.
87     (The default is None)
88
89 Methods
90 -----
91 load_file(filename: Path)
92     -> tuple[np.ndarray, np.ndarray, np.ndarray]
93     Loads the data from a FITS file.
94 get_bounds(bpm: np.ndarray)
95     -> np.ndarray
96     Finds the bounds for the CCD regions.
97 remove_cont(spec: list, wav: list, bpm: list, plotCont: bool)
98     -> None
99     Removes the continuum from the data.
100 correlate(filename1: Path, filename2: Path / None = None)
101    -> None
102    Cross correlates the data.
103 FTCS(filename1: Path, filename2: Path / None = None)
104    -> None
105    Cross correlates the data using the Fourier Transform.
106 plot(spec, wav, bpm, corrdb, lagsdb)
107    -> None
108    Plots the data.
109 process()
110    -> None
111    Processes the data.
112
113 Other Parameters
114 -----
115 offset : int, optional
116     The amount the spectrum is shifted, mainly to test the effect of the cross
117     ↪ correlation
118     (The default is 0, I.E. no offset introduced)
119 **kwargs : dict
120     keyword arguments. Allows for passing unpacked dictionary to the class constructor.
121     FTCS : bool, optional
122         Decides whether the Fourier Transform should be used for cross correlation.
123
124 See Also
125 -----
126 scipy
127     https://docs.scipy.org/doc/scipy/reference/generated/scipy.signal.correlate.html

```

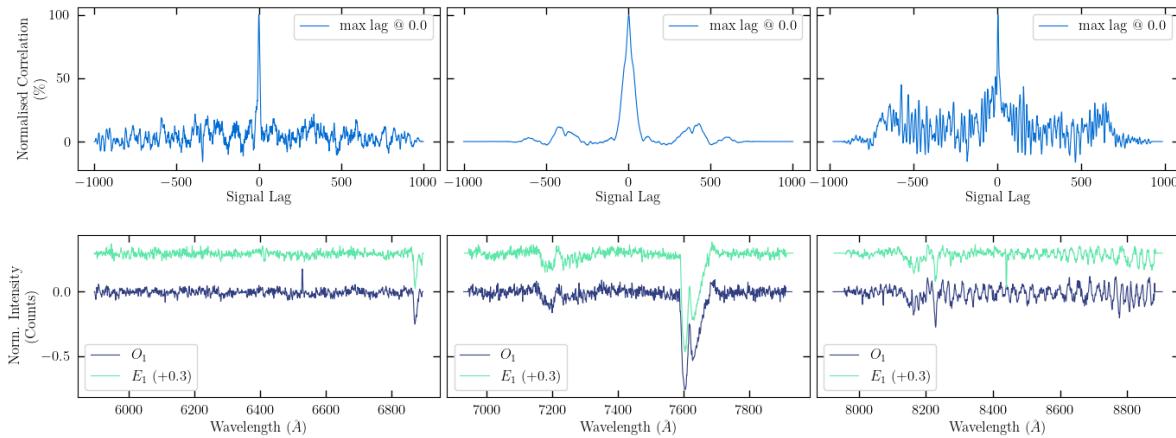


Figure 3.11: The resultant output plot of the `STOPS correlate` method. Figure created via the `STOPS correlate` method.

```

127
128 Notes
129 -----
130 Constants Imported (See utils.Constants):
131   SAVE_CORR
132
133 """

```

The `skyline` method allows for confirmation of a single wavelength solution, but has no means for comparing how the wavelength solutions of two polarization beams differ from each other. The difficulty arises in comparing the two spectra since variations between the two are expected and are what define the Stokes, and thus final polarization, results. The `correlate` method was created for this express purpose.

The `correlate` method loads the provided FITS files created by the POLSALT `spectra extraction`, removes the continuum and separates the CCD regions. The relevant, separated, CCD regions are then cross correlated and any offset between the spectra may be plotted, as seen in Figure 3.11.

As the Stokes results, and thus final polarization results, are determined and are heavily influenced by the differences in the spectra of the different O - and E -beams, a direct comparison is not appropriate. Any observed unpolarized light, however, will reflect equally in both polarization beams and so the general trend of the two spectra may reasonably be expected to follow one another. Cross correlation of the two spectra for the different, O and E , polarization beams allows for a comparison of the features within the spectra as a function of the wavelength displacement.

Sources under spectropolarimetric observation are generally expected to vary over time and, as such, the ratio of polarized to unpolarized light is also expected to vary. The accuracy of correlation may decrease as features with differences in the polarized component of the polarization beams change, and it is up to the user to determine the validity of the correlation result taking into consideration the two spectra being correlated. The differences in the features of the different spectra are often negligible when compared to the overall continuum of the spectra and are generally only reflected in a change in the intensity of said features when the continuum is removed.

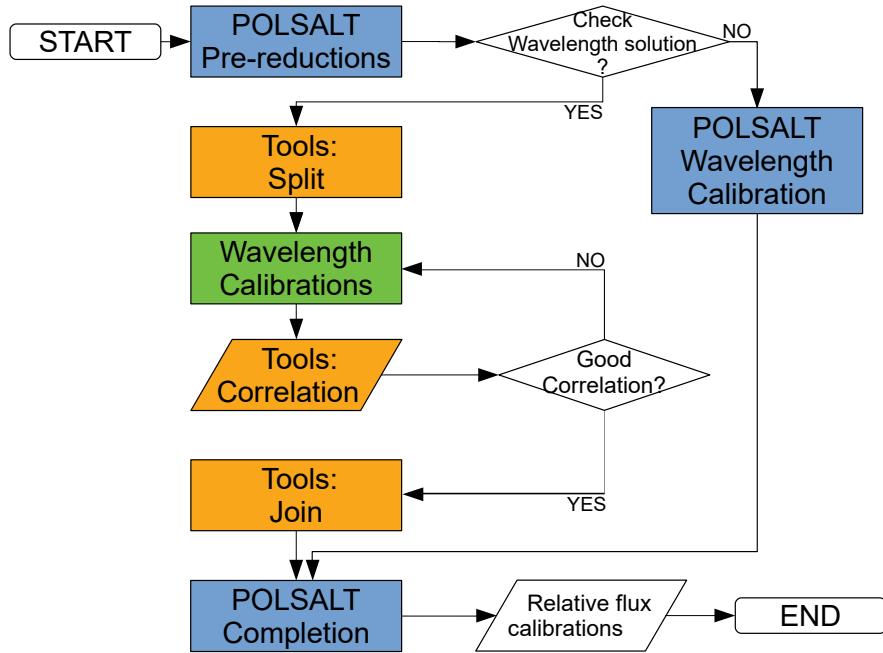


Figure 3.12: A general workflow for data reductions using a combination of POLSLT, IRAF, and the developed supplementary tools. Diagram adapted from Cooper et al. (2022).

Cross correlation is useful when dealing with spectropolarimetric spectra as it allows a comparison of how well aligned the notable features of the spectra are wavelength-wise. Minor deviations between spectra weight the cross correlation less than the more prominent features, and therefore, cross correlation results acquired when using the `correlate` method more accurately reflect any general offset between polarization beams that may not necessarily be found when using the STOPS `skyline` method.

3.4 General Reduction Procedure

This section aims to provide a comprehensive discussion of the modified reduction procedure, an example of which is provided in Appendix I. As users all employ a variety of operating systems, language environments, and software setups, not much emphasis will be placed on how to get the software running or the managing of files: instead, the commands necessary to complete each step of the reduction process are discussed, assuming that the software is running as intended.

One note of importance is that the POLSLT pipeline is not compatible with Python 3, and as such, the CLI must be run in a Python 2 environment. When code Listings are provided (see for example Listing I.1 or the Listing in § 3.4.1 below), the python version to be used is specified as an `anaconda` environment, but a user may use any Python version control method they prefer. The `anaconda` environments are aliased ‘`salt`’ for Python 2 and ‘`stops`’ for Python 3. When no environment is specified, it is assumed the previously specified environment is still active.

It is recommended to use POLSLT through the GUI as it provides a user-friendly en-

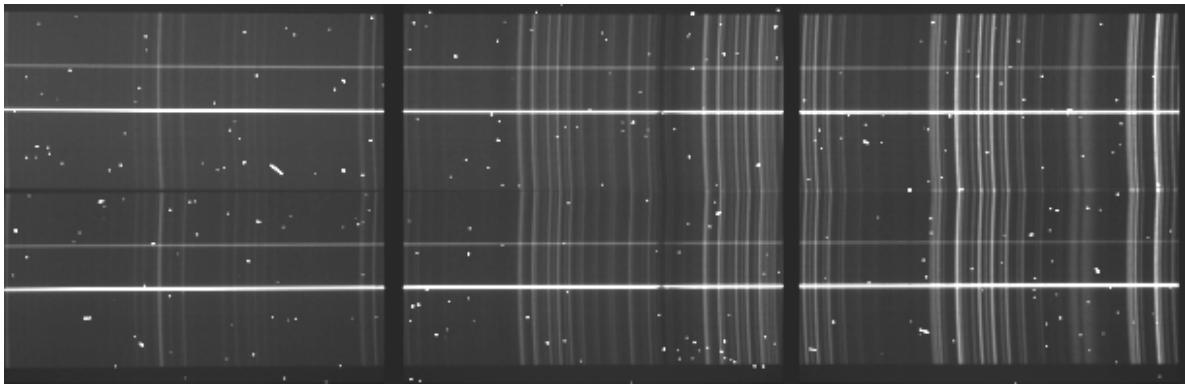


Figure 3.13: The science extension of a typical spectropolarimetric FITS file taken with the SALT RSS, after basic POLSALT CCD reductions have been completed. Figure created from the `STOPs split` output.

vironment while also sequentially listing each step of the reduction process in a dropdown menu, as seen in Figure 3.1. Reductions are possible, however, purely through the CLI using the POLSALT ‘beta’ scripts.

3.4.1 POLSALT Pre-reductions

The POLSALT reduction process requires a file structure such that the raw data received from SALT is located in a folder labelled using the observing date with a sub-folder labelled `raw`, following `YYYYMMDD/raw/`. This directory structure allows POLSALT to create a ‘working’ directory named `YYYYMMDD/sci/` which contains all the files modified during the reduction process. Multiple reduction procedures using the same data may therefore be separated by simply renaming the `sci/` sub-folder.

The POLSALT GUI may be launched by opening a CLI and running Listing I.1. Once the window, depicted in Figure 3.1, has launched, ensure that the first two paths at the top of the window point to the POLSALT and working directories, as seen in Figure 3.1. The ‘raw image reduction’ entry may then be selected from the dropdown and run.

Alternatively, if the data already includes ‘`mxgbp`’ FITS files in the `YYYYMMDD/sci/` working directory, a CLI may be used to complete the initial pre-reductions using

```
$ cd <OBSDATE>/sci
$ conda activate salt
$ python ~/polsalt/scripts/reducepoldata_sc.py <OBSDATE>
```

which will attempt to run the entire reduction process. The script may be quit once the POLSALT wavelength calibration GUI opens, and the rest of the reduction procedure followed.

3.4.2 Wavelength Calibration

The wavelength calibrations may now be completed in IRAF. This section concerns the procedure for parsing the FITS files to be read by IRAF and POLSALT as well as the relevant task names and methods to be run to complete the calibrations. A base working case of each of the tasks and methods are presented in Listing I.2 to I.8, but it should be noted that the art of wavelength calibration consists of modifying the parameters to

achieve a well-fit calibration function. This process depends heavily and varies greatly based on the user and as such not all use cases can be discussed herein.

Preparing the data for IRAF

Splitting the data is presented in Listing I.2. The STOPS `split` method may take multiple parameters, as seen in § 3.3, but default parameters should be used where ever possible. The most notable parameters are the directory, which defaults to the current working directory of the CLI, the split row, which defaults to POLSALT’s default center row, and the save prefix, which defaults to ‘`obeam`’ and ‘`ebeam`’. As an aside, the save prefix may be worth changing as, later in the reduction process, the POLSALT raw Stokes reductions indiscriminately selects files named `YYYYMMDD/sci/e*.fits`, which would include the split ‘`wmxgbp`’ FITS files (`ebeam*.fits`). This naming conflict is revisited and addressed later on in the reduction process and is thus not of any concern.

IRAF wavelength calibrations

The IRAF wavelength calibrations are performed using the tasks described in § 3.2, namely `identify`, `reidentify`, `fitcoords`, and optionally `transform`. In general, these tasks are run directly in the IRAF terminal using:¹⁴

```
cl> identify images
cl> reidentify reference images
cl> fitcoords images fitname
cl> transform images output fitname
```

where ‘`images`’ refer to a list or file containing the FITS files relevant to the task, ‘`reference`’ refers to the FITS file previously identified, ‘`fitname`’ refers to the name to be used for the final two-dimensional wavelength solution, and ‘`output`’ refers to the new file name for the transformed input images.

The interactive tasks take up the bulk of the reduction time as this is where the fine-tuning of the reduction is done, through the use of cursor (or colon) commands, which allow modification of the parameters mid-reduction. Task parameters may, however, be edited beforehand within the IRAF terminal using the `eparam` task, and optionally saved, and quit or run using a combination of `:w`, and `:q` or `:go` cursor commands, respectively.

The reduction process in Appendix I, namely Listing I.4 to I.7, describes how to script the tasks for posterity. It is recommended to create an IRAF Command Language (cl) script for each task to keep track of which parameters were used and for simple recalibrations, but this is not strictly necessary. The scripts are created using the `mkscript` task which interactively asks for a task to script and parameters to use. Multiple tasks may be appended to an IRAF script, allowing for the parameters of both beams to be tracked. Running an IRAF script may be done by running:

```
cl> cl < script_name.cl
```

but is not suggested for interactive scripts, which run best when simply copied from the `<...>/sci/script_name.cl` file to the IRAF terminal.

¹⁴Please see the IRAF help docs, available at https://astro.uni-bonn.de/~sysstw/lfa_html/iraf/iraf.html, on the relevant tasks for a comprehensive discussion of the parameters available.

Preparing the data for POLSALT

The results of the wavelength calibrations may now be parsed back into the format expected by POLSALT. Joining the separate beams with their respective wavelength solutions is once again performed in the CLI following Listing I.8.

Similar to the `split` procedure mentioned above, the `join` procedure has the same defaults defined and so the responsibility falls on a user to keep track of which defaults were changed, and to keep the parameters consistent between the two tasks. Note that STOPS has logging implemented, see § 3.3, and so the onus of tracking the parameters may be passed on to a logging file.

Sky line checks of the wavelength solution

The optional IRAF `transform` task and STOPS `skylines` method are used to confirm the wavelength solution across the frame, as described in § 3.3.3, by transforming and comparing known and observed sky line wavelength positions, respectively.

The `skyline` method is run in the CLI following Listing I.9. The difference in the flux conservation when `skyline` transforms the frames is discussed in § 3.3.3. Otherwise, as with the rest of STOPS, default parameters describe the overplotting behavior for the *O*- and *E*-beams, the skylines provided by SALT, and the calculated variation of the wavelength axis of a frame.

A final reminder is made here about the clash of default naming schemes and the wildcard file collection performed by POLSALT. A simple wildcard ‘`mv`’ move or ‘`rm`’ remove command may be run in the CLI to deal with the created split files used by IRAF. The remove command may be run using:

```
$ rm obeam* ebeam*
```

while moving the files to a new subfolder, which is the recommended course of action, may be done following Listing I.10.

The `correlate` method is run in the CLI following Listing I.11. The input of the `correlate` method takes the output of the POLSALT `spectra extraction` and is thus only run thereafter, but is mentioned here as the completion of the POLSALT reductions is not discussed in much depth. If the user wishes to compare the *O*- and *E*-beams of a single file then only that image name is to be provided, otherwise it is assumed that the user wishes to compare the same polarization beam across each file provided.

3.4.3 POLSALT Reduction Completion

Reductions may now be completed using POLSALT. The reduction process consists of correcting for the wollaston tilt, extracting the spectra, creating the Stokes files, and displaying the results. The ‘beta’ version of POLSALT provides access to a GUI but may also be handled entirely through a CLI as scripts.

POLSALT beta in a GUI

The reduction process using the POLSALT GUI is completed by selecting and, when applicable, interactively modifying the reduction step through the interactive windows, one-by-one, from the GUIs dropdown menu, as explained in Appendix I (pages 65 onwards). As no commands are necessary, save for those to launch the POLSALT GUI, there is not much discussion to be had that is not either covered in § 3.1 or Appendix I. Excellent resources, created by the SALT / SAAO team, are available online for any queries about the reduction process using any version of POLSALT, including the GUI.¹⁵

POLSALT beta through a CLI

Both GUI and CLI implementations of the POLSALT beta pipeline access the same script files. Although the GUI is more user-friendly, the CLI offers a more streamlined approach to the reduction process, allowing the reduction process to be automated once the IRAF wavelength solution is known. The POLSALT beta `reducepoldata_sc.py` script is used to run the entire reduction process, using:

```
$ python reducepoldata_sc.py YYYYMMDD
```

which will run the entire reduction process without needing to select which process to run next. For the purposes of using the script alongside IRAF wavelength calibrations, a few changes must be made to the script file. The `imred` and `specpolwavmap` function calls before `specpolextract_sc` should be commented out, since the raw images have already been processed and the wavelength calibrations were completed using STOPS and IRAF.

The POLSALT beta `reducepoldata_sc.py` copies a `script.py` file into the science working directory, ‘YYYYMMDD/sci/’, which provides analysis scripts for analysis and modification of the POLSALT beta results. These tools consist of data culling for the final Stokes calculations, text and plot output, relative flux calibration corrections, and synthetic filtering of polarization results. The POLSALT analysis scripts may be run using:

```
$ python script.py
```

followed by `specpolfinalstokes.py`, `specpolview.py`, `specpolflux.py`, or `specpolfilter.py`, for the different analysis modes, respectively. A description of the use for each mode of the analysis script is available and is exhaustive enough for general use, with the source code also publically available for further in depth queries or troubleshooting.¹⁶

¹⁵See the official POLSALT wiki or alternative online resources such as the SALT workshop slides.

¹⁶Please see <https://github.com/saltastro/polsalt/wiki/Linear-Polarization-Reduction--Beta-version> for a comprehensive discussion of the POLSALT beta analysis scripts.

Chapter 4

Testing and Application

Short intro to chapter contents.

- No POLSALT or data tests
 - POLSALT is trusted to be accurate. See ... (reference tests of POLSALT)
- Testing `split`
 - POLSALT to IRAF file structure conversion.
 - Show changes to data files are intended (I.E. only splitting the data, no changes to the data itself)
 - Tested over multiple grating/articulation angles to ensure robustness.
 - Mention any header updates skipped specific to POLSALT (if any)
 - Figure showing split fits file contents difference (cropped rows shown, etc.)
- Testing IRAF wavelength solution
 - IRAF is trusted to be accurate. See ... (reference tests of IRAF)
 - The `skylines` and `correlate` outputs are tests of the wavelength calibration.
 - * Testing correlate functionality using ‘offset’, comparisons of arcs, FSRQ’s and BLLac’s.
 - * Any figures showing correlation tests?
 - * Testing skylines using known spectral sky lines.
 - * Any figures showing skyline tests?
- Testing `join`
 - IRAF to POLSALT file structure conversion
 - Show changes to data files are intended (I.E. only joining the data, and ‘WAV’ appended. No changes to the data itself)
 - Wollaston correction of wavelength and bpm extensions
 - update to python 3 of ‘polsalt’ functions
 - Mention any header differences (if any)
 - Figure showing joined fits file contents difference (cropped rows shown once again, bpm differences due to CRR and NO wollaston bpm differences, etc.)
- Testing reduction results not negatively impacted by STOPS.
 - General discussion of testing (I.E. not this test was done specifically this source, more along the lines of these tests were done to check this issue, seen here using this source for example.)

- Wavelength solution validation from correlate and skylines results.
 - * Figures showing Correlate and Skyline results.
 - * RMS comparisons between POLSALT and IRAF to quantify differences.
 - * Any Figures for RMS comparisons or wavelength validation?
- Polarization parameters validation from known sources.
 - * Polarization tested using 3C 279, 4C+01.02, and preliminary testing data provided by David.
 - * Polarization tested using spectropolarimetric standards (4 highly polarized, 2 non-polarized).
 - * Tabulate sources used, with their properties.
 - * Figures showing comparison plots of polarization parameters from POLSALT and STOPS.
- Background information on each object.
- Detailed reductions steps performed on each object.
- Comparison of POLSALT results to those obtained using the STOPS pipeline.
- Application to Spectropolarimetric Standards
 - Science results, what the results can tell us and why it is useful, also comparison of results to FORS1/2 published data, focus on the polarization results.
- Application in Publications
 - Summarize the results of the publications appended to appendix.

Chapter 5

Science Applications

TODO: Short introduction to chapter contents

5.1 Application to Spectropolarimetric Standards

TODO: Spectropolarimetric standards (4 highly polarized, 2 non-polarized)

- (Same as ch04 with science results)
- Background on objects
- Reductions
- Actual results - comparison of polsalt results to supplementary pipeline results
- Science results, what the results can tell us and why it is useful, also comparison of results to FORS1/2 published data, focus on the polarization results

5.2 Application in publications

TODO: Summary of results from papers in appendix.

- Hester paper(s)
- Joleen proceedings and work
- My proceedings

TODO: 3C 279 and 4C+01.02

- Give Background on objects, Reduction steps, and Science results (what the results can tell us and why it is useful)
- (comparison of polsalt results to supplementary pipeline results will be in testing)

Chapter 6

Conclusions

TODO: A summary of the dissertation, main focus on the results and that the supplementary pipeline is a success since it allows an alternate method using IRAF to wavelength calibrate the polsalt data.

Appendix I

The Modified Reduction Process

This section of the Appendix aims to provide a minimum working example of the commands necessary to reduce POLSALT data using STOPS and IRAF. It contains the commands necessary to activate all software and run through the reduction process but makes no attempt at discussion.

Both POLSALT and IRAF are launched from the default CLI but use independent interfaces during the reduction process. To distinguish which window is in focus, the ‘\$’ token is used for default CLI commands while the ‘c1>’ and ‘>>>’ tokens are used for IRAF’s ‘xgterm’ single- and multi-line commands, respectively.

General instructions for the reduction process which might not necessarily be line-fed commands passed to a CLI may either be discussed outside a ‘Listing’ environment or included as part of the ‘Listing’ environment with a preceding ‘#’ token. Finally, POLSALT implements a GUI and thus takes no line-fed commands. As such, the instructions when using the POLSALT GUI follow those of the general instructions with the added exception that they relate to the GUI.

As a final note, some parameters are distinguished using an ‘<angle brackets>’ notation. They signify necessary parameters that may vary from reduction to reduction. Notable uses of this notation include the date of observation, $\langle OBSDATE \rangle$ (formatted ‘YYYYMMDD’), the split science FITS files, $\langle O\text{-beam FILES} \rangle$ or $\langle E\text{-beam FILES} \rangle$, the split arc FITS files, $\langle O\text{-beam ARC} \rangle$ or $\langle E\text{-beam ARC} \rangle$, and a wildcard symbol, $\langle * \rangle$.

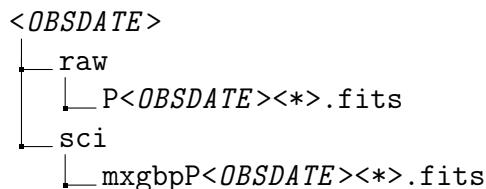


Figure I.1: The typical minimal file structure of data provided by SALT.

Ensure the data is formatted in a file structure similar to that in Figure I.1. Data located in the ‘sci’ folder is often provided by SALT but is not strictly necessary to begin the reduction process. If ‘mxgbp’ prefixed data is available, the reductions may be begun starting at Listing I.2. The POLSALT GUI is launched from the default CLI running the commands in Listing I.1.

Listing I.1: Launching the POLSALT GUI

```
$ cd ~/polsalt
$ conda activate salt
$ python -W ignore reducepoldataGUI.py &
```

Refer to Figure 3.1 for a depiction of the POLSALT GUI. To complete the POLSALT pre-calibrations, and with the GUI in focus:

- Ensure that the ‘POLSALT code directory’ is correct.
- Set the ‘Top level data directory’ to $\langle OBSDATE \rangle$.
- Ensure ‘Raw data directory’ is correct.
- Ensure ‘Science data directory’ is correct.
- Select ‘Raw image reduction’ from the ‘Data reduction step’ drop down menu.
- Check the tick boxes of all raw images to be processed (include the arc) in the display box covering the lower half of the GUI.
- Proceed with the reductions by clicking the ‘OK’ button.

The pre-calibrated ‘mxgbp’ FITS files are now available in the ‘sci’ folder. The files may be split using STOPS by running the commands in Listing I.2.

Listing I.2: Splitting data using STOPS

```
$ cd <OBSDATE>/sci
$ conda activate stops
$ python ~/STOPS . split
```

The split *O*- and *E*-beam FITS files are now available. The IRAF wavelength calibrations are now run. The IRAF xgterm CLI is launched using Listing I.3.

Listing I.3: Launching IRAF in xgterm

```
$ cd ~/iraf
$ xgterm -sb &
cl> conda activate salt
cl> cl
cl> noao
cl> twodspec
cl> longslit
cl> unlearn longslit
cl> longslit.dispaxis=1
```

The IRAF `identify` task requires an average feature width, ‘fwidth’, as a parameter. The width of a feature may be found in IRAF using the `implot` task¹ along with cursor

¹See https://astro.uni-bonn.de/~sysstw/lfa_html/iraf/plot.implot.html for documentation on the `implot` task.

commands, but may also be found using FITS viewing software, such as `ds9`.² The `identify` task may be run using the commands in Listing I.4.

Listing I.4: Running the IRAF `identify` task

```
cl> mkscript 01_identify.cl
cl> # Add identify to 01_identify.cl twice, for both beams
cl> # Edit the parameters of 01_identify.cl in a text editor
cl> # Paste an identify script into the CLI, resulting in:
cl>
cl> identify ("<O-beam ARC>",
>>> "", "", section="middle line", database="database",
>>> coordlist="linelists$idheneare.dat", units="", nsum="10", match=-3.,
>>> maxfeatures=50, zwidth=100., ftype="emission", fwidth=8.,
>>> cradius=5., threshold=0., minsep=2., function="spline3", order=2,
>>> sample="*", niterate=0, low_reject=3., high_reject=3., grow=0.,
>>> autowrite=no, graphics="stdgraph", cursor="", aidpars="")
```

The `identify` task will launch an interactive window. Cursor commands refer to keys that provide unique functionality to the interactive IRAF tasks. The cursor commands for `identify` allow the arc lines to be identified using ‘m’ (and typing the relevant wavelength), while ‘d’ and ‘i’ will delete a single and all identified arc lines, respectively. The ‘f’ cursor command will perform a preliminary fit which can be quit using the ‘q’ cursor command. The ‘l’ cursor command will attempt to identify any unidentified arc lines. Once complete, a figure of the identified lines may be saved using ‘:labels coord’ and ‘:.snap eps’, and the task safely quit with the ‘q’ cursor command.³ The `identify` procedure is repeated, replacing `<O-beam ARC>` with `<E-beam ARC>`.

The `reidentify` task may be run using the commands in Listing I.5.

Listing I.5: Running the IRAF `reidentify` task

```
cl> mkscript 02_reidentify.cl
cl> # Add reidentify to 02_reidentify.cl twice, for both beams
cl> # Edit the parameters of 02_reidentify.cl in a text editor
cl> # Paste a reidentify script into the CLI, resulting in:
cl>
cl> reidentify ("<O-beam ARC>",
>>> "<O-beam ARC>", "yes", "", "", interactive="no", section="middle
>>> line", newaps=yes, override=no, refit=yes, trace=yes, step="10",
>>> nsum="10", shift="0.", search=0., nlost=0, cradius=5.,
>>> threshold=0., addfeatures=no, coordlist="linelists$idheneare.dat",
>>> match=-3., maxfeatures=50, minsep=2., database="database",
>>> logfiles="logfile", plotfile="", verbose=yes, graphics="stdgraph",
>>> cursor="", aidpars="")
```

The `reidentify` task will run autonomously so long as the `interactive` parameter is set to “no”.⁴ Repeat the `reidentify` procedure, replacing `<O-beam ARC>` with `<E-beam ARC>` at both the ‘reference’ and ‘image’ parameter locations.

²See <https://sites.google.com/cfa.harvard.edu/saoimageds9> for documentation on the `ds9` software.

³See https://astro.uni-bonn.de/~sysstw/lfa_html/iraf/noao.onedspec.identify.html for documentation on the `identify` task.

⁴See https://astro.uni-bonn.de/~sysstw/lfa_html/iraf/noao.onedspec.reidentify.html for documentation on the `reidentify` task.

The `fitcoords` task may be run using the commands in Listing I.6.

Listing I.6: Running the `IRAF fitcoords` task

```
cl> mkscript 03_fitcoords.cl
cl> # Add fitcoords to 03_fitcoords.cl twice, for both beams
cl> # Edit the parameters of 03_fitcoords.cl in a text editor
cl> # Paste a fitcoords script into the CLI, resulting in:
cl>
cl> fitcoords ("<O-beam ARC> (exclude the file extension)",
>>> fitname="", interactive=yes, combine=no, database="database",
>>> deletions="deletions.db", function="chebyshev", xorder=6, yorder=6,
>>> logfiles="STDOUT,logfile", plotfile="plotfile",
>>> graphics="stdgraph", cursor="")
```

The `fitcoords` task will launch an interactive window. The x- and y-axis being plotted may be changed using the ‘x’ or ‘y’ cursor commands followed by the desired data axis (‘x’ for the x-axis, ‘y’ for the y-axis, or ‘r’ for the residuals).⁵ Repeat the `fitcoords` procedure, replacing $<O\text{-beam } ARC>$ with $<E\text{-beam } ARC>$.

The `transform` task may be run using the commands in Listing I.7.

Listing I.7: Running the `IRAF transform` task

```
cl> mkscript 04_transform.cl
cl> # Add transform to 04_transform.cl twice, for both beams
cl> # Edit the parameters of 04_transform.cl in a text editor
cl> # Paste a transform script into the CLI, resulting in:
cl>
cl> transform ("@<O-beam FILES>",
>>> "t//@<O-beam FILES>", "<O-beam ARC> (exclude the file extension)",
>>> minput="", moutput="", database="database", interptype="linear",
>>> x1="INDEF", x2="INDEF", dx="INDEF", nx="INDEF", xlog="no",
>>> y1="INDEF", y2="INDEF", dy="INDEF", ny="INDEF", ylog="no",
>>> flux="yes", blank="INDEF", logfiles="STDOUT,logfile")
```

Inspect the transformed images, most notably the arc images, using any FITS viewer as a cursory check that the wavelength calibrations were completed without error.⁶

The ‘gain’ and ‘read noise’ are now needed as the cosmic-ray rejection of the STOPS `join` method accepts them as parameters. These parameters may be found using the ‘*GAINSET*’ and ‘*ROSPEED*’ keywords in the FITS headers. The cosmic ray rejection defaults to *GAINSET*=‘FAINT’, and *ROSPEED*=‘SLOW’. If the gain and read noise values differ from the defaults, the parameters should be updated when running `join`.⁷

⁵See https://astro.uni-bonn.de/~sysstw/lfa_html/iraf/noao.twodspec.longslit.fitcoords.html for documentation on the `fitcoords` task.

⁶See https://astro.uni-bonn.de/~sysstw/lfa_html/iraf/noao.twodspec.longslit.transform.html for documentation on the `transform` task.

⁷The read noise and gain may be determined from http://pysalt.salt.ac.za/proposal_calls/current/ProposalCall.html, specifically Table 6.1 and Table 6.2.

The STOPS `join` method may be run using the commands in Listing I.8.

Listing I.8: Joining the data using STOPS

```
$ cd <OBSDATE>/sci
$ conda activate stops
$ python ~/STOPS . join
```

The STOPS `skylines` method may be run on any ‘joined’ or transformed FITS files, $\langle FILE(S) \rangle$, using the commands in Listing I.9.

Listing I.9: Running the STOPS `skylines` method

```
$ cd <OBSDATE>/sci
$ conda activate stops
$ python ~/STOPS . skylines <FILE(S)>
```

The ‘`sci/`’ directory may now be slightly organized by running the commands in Listing I.10, moving all the files relevant to the wavelength calibrations into either the ‘`database`’ or ‘`split_files`’ directories.

Listing I.10: Directory cleanup for POLSALT

```
$ cd <OBSDATE>/sci
$ mkdir split_files
$ mv *beam0* *beamE* *arc0* *arcE* split_files/
$ mv *.eps *.cl *.db database/
```

The POLSALT `spectra extraction` is now run. If the POLSALT GUI was closed it should now be reopened using Listing I.1. With the GUI in focus:

- Ensure all directories are still correct.
- Select ‘Spectra extraction’ from the ‘Data reduction step’ drop down menu.
- Check the tick boxes of all wavelength calibrated images to be processed (exclude the arc) in the display box covering the lower half of the GUI.
- Proceed with the reductions by clicking ‘OK’.

The POLSALT `spectra extraction` is interactive and will launch a separate GUI for the background subtraction and spectral extraction (see Figure 3.2). The background and spectral regions to be extracted may be adjusted, noting that adjustments affect both *O*- and *E*-beams. Once both background regions contain no trace and the spectral region fully contains only the science trace, the reduction may be completed by clicking ‘OK’.

The STOPS `correlate` method may now be run on any ‘joined’ FITS files by running the commands in Listing I.11.

Listing I.11: Running the STOPS `correlate` method

```
$ cd <OBSDATE>/sci
$ conda activate stops
$ python ~/STOPS . correlate <FILE(S)>
```

The POLSALT **raw Stokes calculation**, **final Stokes calculation**, and **results visualisation** may now be completed. For the last time, if the POLSALT GUI was closed it should now be reopened using Listing I.1. With the GUI in focus:

- Ensure all directories are still correct.
- Select ‘Raw Stokes calculation’ from the ‘Data reduction step’ drop down menu.
- Check the tick boxes of all the extracted spectra images to be processed in the display box covering the lower half of the GUI.
- Proceed with the **raw Stokes calculation** by clicking ‘OK’.
- Select ‘Final Stokes calculation’ from the ‘Data reduction step’ drop down menu.
- Check the tick boxes of all the “raw Stokes” images to be processed in the display box covering the lower half of the GUI.
- Proceed with the **Final Stokes calculation** by clicking ‘OK’.
- Select ‘Results visualisation - interactive’ from the ‘Data reduction step’ drop down menu.
- Check the tick boxes of the “final Stokes” image to be visualized in the display box covering the lower half of the GUI.
- Proceed with the **visualisation** by clicking ‘OK’.

The POLSALT **visualisation** is interactive and will launch a separate GUI (See Figure 3.3). The GUI may be used to change the binning and parameters of the plot before saving the plot to a PDF file.

This concludes the minimum working example of the POLSALT reduction process when substituting the POLSALT **wavelength calibrations** with those done in IRAF. Aside from the final results, the file structure after reductions should resemble something akin to that provided in Figure I.2.

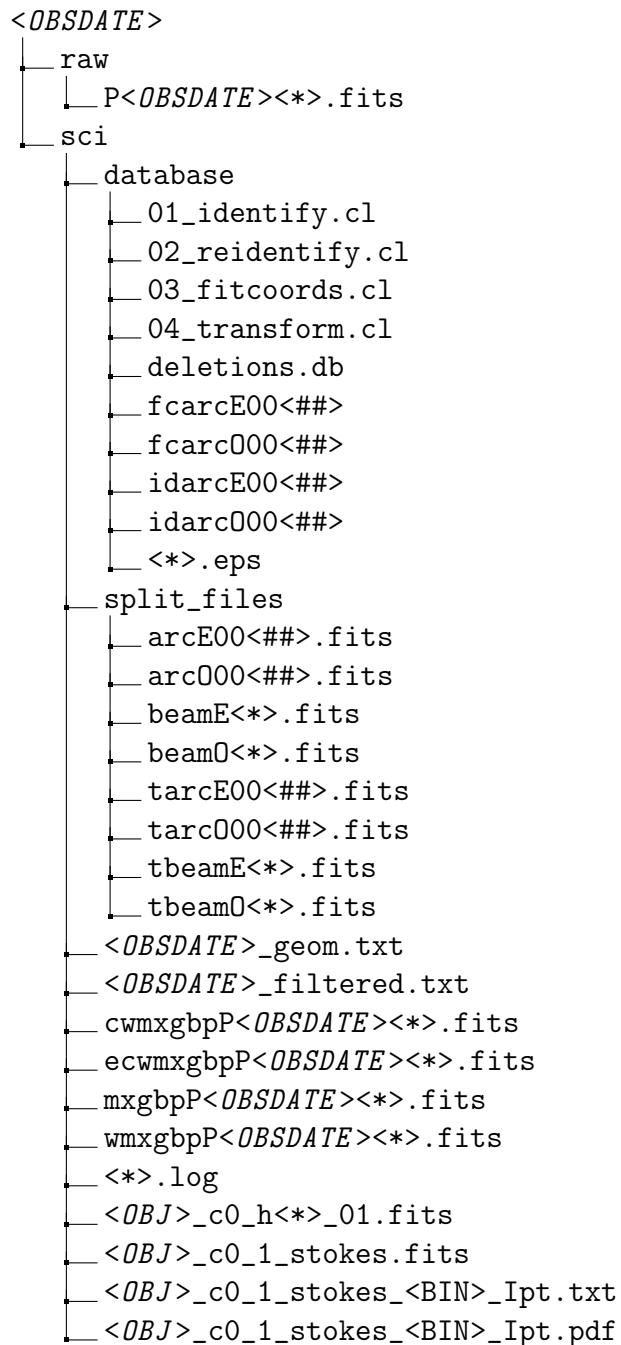


Figure I.2: The typical file structure after completing the reduction process.

Appendix II

STOPS Source Code

This section of Appendix includes all the major STOPS source code files related to the reduction process. Files such as those related to python initialization, testing directories, and other non-essential modules have been excluded for brevity and clarity.

Listing II.1: The source code for `__main__.py`

```
1 """Argument parser for STOPS."""
2
3 #!/usr/bin/env python3
4 # -*- coding: utf-8 -*-
5
6 from __init__ import __version__, __author__, __email__
7
8 # MARK: Imports
9 import os
10 import sys
11 import argparse
12 import logging
13 from pathlib import Path
14
15 from split import Split
16 from join import Join
17 from cross_correlate import CrossCorrelate
18 from skylines import Skylines
19
20 from utils import ParserUtils as pu
21 from utils.Constants import SPLIT_ROW, PREFIX, PARSE, SAVE_CORR,
22   ↪ SAVE_SKY
23
24 # MARK: Constants
25 PROG = "STOPS"
26 DESCRIPTION = """
27 Supplementary Tools for Polsalt Spectropolarimetry (STOPS) is a
28 collection of supplementary tools created for SALT's POLSALT pipeline,
29 allowing for wavelength calibrations with IRAF. The tools provide
30 support for splitting and joining polsalt formatted data as well as
31 cross correlating complementary polarimetric beams.
32 DOI: 10.22323/1.401.0056
```

```

33 """
34
35
36 # MARK: Universal Parser
37 parser = argparse.ArgumentParser(
38     prog=PROG,
39     description=DESCRIPTION,
40     formatter_class=argparse.RawDescriptionHelpFormatter,
41 )
42 parser.add_argument(
43     "-V",
44     "--version",
45     action="version",
46     version=f"%(prog)s as of {__version__}",
47 )
48 parser.add_argument(
49     "-v",
50     "--verbose",
51     action="count",
52     default=PARSE['VERBOSE'],
53     help=(
54         "Counter flag which enables and increases verbosity. "
55         "Use -v or -vv for greater verbosity levels."
56     ),
57 )
58 parser.add_argument(
59     "-l",
60     "--log",
61     action="store",
62     type=pu.parse_logfile,
63     help=(
64         "Filename of the logging file. "
65         "File is created if it does not exist. Defaults to None."
66     ),
67 )
68 parser.add_argument(
69     "data_dir",
70     action="store",
71     nargs="?",
72     default=PARSE['DATA_DIR'],
73     type=pu.parse_path,
74     help=(
75         "Path of the directory which contains the working data. "
76         f"Defaults to the cwd -> '{PARSE['DATA_DIR']}' (I.E. '.')."
77     ),
78 )
79
80
81 # MARK: Split\Join Parent
82 split_join_args = argparse.ArgumentParser(add_help=False)
83 split_join_args.add_argument(
84     "-n",
85     "--no_arc",
86     action="store_true",
87     help="Flag to exclude arc files from processing.",
88 )
89 split_join_args.add_argument(
90     "-s",

```

```

91     "--split_row",
92     default=SPLIT_ROW,
93     type=int,
94     help=(
95         "Row along which the O and E beams are split. "
96         f"Defaults to polsalt's default -> {SPLIT_ROW}.""
97     ),
98 )
99 split_join_args.add_argument(
100    "-p",
101    "--save_prefix",
102    nargs=2,
103    default=PREFIX,
104    help=(
105        "Prefix appended to the filenames, "
106        "with which the O and E beams are saved. "
107        f"Defaults to {PREFIX}.""
108    ),
109 )
110
111
112 # MARK: Correlate\Skylines Parent
113 corr_sky_args = argparse.ArgumentParser(add_help=False)
114 corr_sky_args.add_argument(
115    "filenames",
116    action="store",
117    nargs="+",
118    type=pu.parse_file,
119    help=(
120        "File name(s) of FITS file(s) to be processed."
121        "A minimum of one filename is required."
122    ),
123 )
124 corr_sky_args.add_argument(
125    "-b",
126    "--beams",
127    choices=["O", "E", "OE"],
128    type=str.upper,
129    default=PARSE['BEAMS'],
130    help=(
131        "Beams to process. "
132        f"Defaults to {PARSE['BEAMS']}, but "
133        "may be given 'O', 'E', or 'OE' to "
134        "determine which beams are processed."
135    ),
136 )
137 corr_sky_args.add_argument(
138    "-ccd",
139    "--split_ccd",
140    action="store_false",
141    help=(
142        "Flag to NOT split CCD's. "
143        "Recommended to leave off unless the chip gaps "
144        "have been removed from the data."
145    ),
146 )
147 corr_sky_args.add_argument(
148    "-c",

```

```

149     "--continuum_order",
150     type=int,
151     default=PARSE['CONT_ORD'],
152     dest="cont_ord",
153     help=(
154         "Order of continuum to remove from spectra. "
155         "Higher orders recommended to remove most variation, "
156         "leaving only significant features."
157     ),
158 )
159 corr_sky_args.add_argument(
160     "-p",
161     "--plot",
162     action="store_true",
163     help="Flag for additional plot outputs.",
164 )
165 corr_sky_args.add_argument(
166     "-s",
167     "--save_prefix",
168     action="store",
169     nargs="?",
170     type=lambda path: Path(path).expanduser().resolve(),
171     const=SAVE_CORR,
172     help=(
173         "Prefix used when saving plot. "
174         "Excluding flag does not save output plot, "
175         f"flag usage of option uses default prefix, "
176         "and a provided prefix overwrites default prefix."
177     ),
178 )
179
180
181 # MARK: Create subparser modes
182 subparsers = parser.add_subparsers(
183     dest="mode",
184     help="Operational mode of supplementary tools",
185 )
186
187
188 # MARK: Split Subparser
189 split_parser = subparsers.add_parser(
190     "split",
191     aliases=["s"],
192     help="Split mode",
193     parents=[split_join_args],
194 )
195 # 'children' split args here
196 # Change defaults here
197 split_parser.set_defaults(
198     mode="split",
199     func=Split,
200 )
201
202
203 # MARK: Join Subparser
204 join_parser = subparsers.add_parser(
205     "join",
206     aliases=["j"],

```

```

207     help="Join mode",
208     parents=[split_join_args],
209 )
210 # 'children' join args here
211 join_parser.add_argument(
212     "-c",
213     "--coefficients",
214     dest="solutions_list",
215     nargs='*',
216     type=pu.parse_file,
217     help=(
218         "Custom coefficients to use instead of the `IRAF` fitcoords "
219         "database. Use as either '-c <o_solution> <e_solution>' or "
220         "a regex descriptor '-c <*solution*extention>'."
221     ),
222 )
223 # Change defaults here
224 join_parser.set_defaults(
225     mode="join",
226     func=Join,
227 )
228
229
230 # MARK: Correlate Subparser
231 corr_parser = subparsers.add_parser(
232     "correlate",
233     aliases=["x"],
234     help="Cross correlation mode",
235     parents=[corr_sky_args],
236 )
237 # 'children' join args here
238 corr_parser.add_argument(
239     "-o",
240     "--offset",
241     type=int,
242     default=PARSE['OFFSET'],
243     help=(
244         "Introduces an offset when correcting for "
245         "known offset in spectra or for testing purposes. "
246         f"Defaults to {PARSE['OFFSET']}. "
247         "(For testing, not used during regular operation.)"
248     ),
249 )
250 # Change defaults here
251 corr_parser.set_defaults(
252     mode="correlate",
253     func=CrossCorrelate,
254 )
255
256
257 # MARK: Skyline Subparser
258 sky_parser = subparsers.add_parser(
259     "skylines",
260     aliases=["sky"],
261     help="Sky line check mode",
262     parents=[corr_sky_args],
263 )
264 # 'children' skyline args here

```

```

265 sky_parser.add_argument(
266     "-t",
267     "--transform",
268     action="store_false",
269     help=(
270         "Flag to force transform images. "
271         "Recommended to use only when input image(s) "
272         "are prefixed 't' but are not yet transformed."
273     ),
274 )
275 # Change defaults here
276 sky_parser.set_defaults(
277     mode="skyline",
278     func=Skylines,
279 )
280
281
282 # MARK: Keyword Clean Up
283 args = parser.parse_args()
284
285 if len(sys.argv) == 1:
286     parser.print_help(sys.stderr)
287     sys.exit(2)
288
289 args.verbose = pu.parse_loglevel(args.verbose)
290
291 if 'log' in args and args.log not in [None]:
292     args.log = args.data_dir / args.log
293
294 if "filenames" in args:
295     args.filenames = pu.flatten(args.filenames)
296
297 if "solutions_list" in args and type(args.solutions_list) == list:
298     args.solutions_list = pu.flatten(args.solutions_list)
299
300 # MARK: Begin logging
301 logging.basicConfig(
302     filename=args.log,
303     format"%(asctime)s - %(module)s - %(levelname)s - %(message)s",
304     datefmt="%Y-%m-%d %H:%M:%S",
305     level=args.verbose,
306 )
307
308 # MARK: Call Relevant Class(Args)
309 logging.debug(f"Argparse namespace: {args}")
310 logging.info(f"Mode:{args.mode}")
311 args.func(**vars(args)).process()
312
313
314 # Confirm all processes completed and exit without error
315 logging.info("All done! Come again!\n")

```

Listing II.2: The source code for `split.py`

```

1  """Module for splitting ``polsalt`` FITS files."""
2
3 #!/usr/bin/env python3
4 # -*- coding: utf-8 -*-
5
6 from __init__ import __author__, __email__, __version__
7
8 # MARK: Imports
9 import os
10 import sys
11 import logging
12 from copy import deepcopy
13 from pathlib import Path
14
15 import numpy as np
16 from astropy.io import fits as pyfits
17
18 from utils.SharedUtils import find_files, find_arc
19 from utils.Constants import SAVE_PREFIX, CROP_DEFAULT, SPLIT_ROW
20
21
22 # MARK: Split Class
23 class Split:
24
25     #-----split0-----
26
27     """
28     The `Split` class allows for the splitting of `polsalt` FITS files
29     based on the polarization beam. The FITS files must have basic
30     `polsalt` pre-reductions already applied (`mxgbp...` FITS files).
31
32     Parameters
33     -----
34     data_dir : str
35         The path to the data to be split
36     fits_list : list[str], optional
37         A list of pre-reduced `polsalt` FITS files to be split within `data_dir`.
38         (The default is None, `Split` will search for `mxgbp*.fits` files)
39     split_row : int, optional
40         The row along which to split the data of each extension in the
41         FITS file.
42         (The default is SPLIT_ROW (See Notes), the SALT RSS CCD's
43         middle row)
44     no_arc : bool, optional
45         Decides whether the arc frames should be recombined.
46         (The default is False, `polsalt` has no use for the arc after
47         wavelength calibrations)
48     save_prefix : dict[str, list[str]], optional
49         The prefix with which to save the O & E beams.
50         Setting `save_prefix` = ``None`` does not save the split O & E
51         beams.
52         (The default is SAVE_PREFIX (See Notes))
53
54     Attributes
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```

```

51      -----
52      arc : str
53          Name of arc FITS file within `data_dir`.
54          `arc` = `""` if `no_arc` or not detected in `data_dir`.
55      o_files, e_files : list[str]
56          A list of the `O`- and `E`-beam FITS file names.
57          The first entry is the arc file if `arc` defined.
58      data_dir
59      fits_list
60      split_row
61      save_prefix
62
63  Methods
64  -----
65  split_file(file: os.PathLike)
66      -> tuple[astropy.io.fits.HDUList]
67          Handles creation and saving the separated FITS files
68  split_ext(hdulist: astropy.io.fits.HDUList, ext: str = 'SCI')
69      -> astropy.io.fits.HDUList
70          Splits the data in the `ext` extension along the `split_row`.
71  crop_file(hdulist: astropy.io.fits.HDUList, crop: int =
72      ↪ CROP_DEFAULT (See Notes))
73      -> tuple[numpy.ndarray]
74          Crops the data along the edge of the frame, that is,
75          `O`-beam cropped as [crop:], and
76          `E`-beam cropped as [: - crop].
77  update_beam_lists(o_name: str, e_name: str)
78      -> None
79          Updates `o_files` and `e_files`.
80  save_beam_lists(file_suffix: str = 'frames')
81      -> None
82          Creates (Overwrites if exists) and writes the `o_files` and `e_files` to files named
83          `o_{file_suffix}` and `e_{file_suffix}`, respectively.
84  process()
85      -> None
86          Calls `split_file` and `save_beam_lists` on each file in `fits_list` for automation.
87
88  Other Parameters
89  -----
90  **kwargs : dict
91      keyword arguments. Allows for passing unpacked dictionary to
92      ↪ the class constructor.
93
94  Notes
95  -----
96  Constants Imported (See utils.Constants):
97      SAVE_PREFIX
98      CROP_DEFAULT
99      SPLIT_ROW
100
101      """
102  #-----split1-----
103  # MARK: Split init
104  def __init__(


```

```

105     self,
106     data_dir: Path,
107     fits_list: list[str] = None,
108     split_row: int = SPLIT_ROW,
109     no_arc: bool = False,
110     save_prefix: Path | None = None,
111     **kwargs
112 ) -> None:
113     self.data_dir = data_dir
114     self.fits_list = find_files(
115         data_dir=data_dir,
116         filenames=fits_list,
117         prefix="mxgbp",
118         ext="fits"
119     )
120     self.split_row = split_row
121     self.save_prefix = SAVE_PREFIX
122     if type(save_prefix) == dict:
123         self.save_prefix = save_prefix
124
125     self.arc = "" if no_arc else find_arc(self.fits_list)
126     self.o_files = []
127     self.e_files = []
128
129     logging.debug(f"__init__ - \n{self.__dict__}")
130     return
131
132 # MARK: Split Files
133 def split_file(
134     self,
135     file: os.PathLike
136 ) -> tuple[pyfits.HDUList]:
137     """
138         Split the single FITS file into separated `O`- and `E`- FITS
139         files.
140
141     Parameters
142     -----
143     file : os.PathLike
144         The name of the FITS file to be split.
145
146     Returns
147     -----
148     tuple[astropy.io.fits.HDUList]
149         Tuple containing the split O and E beam HDULists.
150
151     """
152     # Create empty HDUList
153     O_beam = pyfits.HDUList()
154     E_beam = pyfits.HDUList()
155
156     # Open file and split O & E beams
157     with pyfits.open(file) as hdul:
158         O_beam.append(hdul["PRIMARY"].copy())
159         E_beam.append(hdul["PRIMARY"].copy())
160
161         # Split specific extention
162         raw_split = self.split_ext(hdul, "SCI")

```

```

162
163     # O_beam[0].data = raw_split['SCI'].data[1]
164     # E_beam[0].data = raw_split['SCI'].data[0]
165     O_beam[0].data, E_beam[0].data = self.crop_file(raw_split)
166
167     # Handle prefix and names
168     pref = "arc" if file == self.arc else "beam"
169     o_name = self.save_prefix[pref][0] + file.name[-9:]
170     e_name = self.save_prefix[pref][1] + file.name[-9:]
171
172     # Add split data to O & E beam lists
173     self.update_beam_lists(o_name, e_name, pref == "arc")
174
175     # Handle don't save case
176     if self.save_prefix == None:
177         return O_beam, E_beam
178
179     # Handle save case
180     O_beam.writeto(o_name, overwrite=True)
181     E_beam.writeto(e_name, overwrite=True)
182
183     return O_beam, E_beam
184
185     # MARK: Split extensions
186 def split_ext(
187     self,
188     hdulist: pyfits.HDUList,
189     ext: str = "SCI"
190 ) -> pyfits.HDUList:
191     """
192         Split the data of the specified extension of `hdulist` into its
193         → `O`- and `E`- beams.
194
195         Parameters
196         -----
197         hdulist : astropy.io.fits.HDUList
198             The FITS HDUList to be split.
199         ext : str, optional
200             The name of the extension to be split.
201             (Defaults to 'SCI')
202
203         Returns
204         -----
205         astropy.io.fits.HDUList
206             The HDUList with the split applied.
207
208         """
209         hdu = deepcopy(hdulist)
210         rows, cols = hdu[ext].data.shape
211
212         # if odd number of rows, strip off the last one
213         rows = int(rows / 2) * 2
214
215         # how far split is from center of detector
216         offset = int(self.split_row - rows / 2)
217
218         # split arc into o/e images
219         ind_rc = np.indices((rows, cols))[0]

```

```

219     padbins = (ind_rc < offset) | (ind_rc > rows + offset)
220
221     # Roll split_row to be centre row
222     image_rc = np.roll(hdu[ext].data[:rows, :], -offset, axis=0)
223     image_rc[padbins] = 0.0
224
225     # Split columns equally
226     hdu[ext].data = image_rc.reshape((2, int(rows / 2), cols))
227
228     return hdu
229
230
231     # MARK: Crop files
232     def crop_file(
233         self,
234         hdulist: pyfits.HDUList,
235         crop: int = CROP_DEFAULT
236     ) -> tuple[np.ndarray]:
237         """
238             Crop the data with respect to the `O`/`E` beam.
239
240             Parameters
241             -----
242             hdulist : astropy.io.fits.HDUList
243                 The HDUList containing the data to be cropped.
244             crop : int, optional
245                 The number of rows to be cropped from the bottom and top
246                 of the `O` and `E` beam, respectively.
247                 (Defaults to 40)
248
249             Returns
250             -----
251             tuple[numpy.ndarray]
252                 Tuple containing the cropped O and E beam data arrays.
253
254             """
255             o_data = hdulist["SCI"].data[1, 0:-crop]
256             e_data = hdulist["SCI"].data[0, crop:]
257
258             return o_data, e_data
259
260     # MARK: Update beam lists
261     def update_beam_lists(
262         self,
263         o_name,
264         e_name,
265         arc: bool = True
266     ) -> None:
267         """
268             Update the `o_files` and `e_files` attributes.
269
270             Parameters
271             -----
272             o_name : str
273                 The filename of the O beam.
274             e_name : str
275                 The filename of the E beam.
276             arc : bool, optional
277                 Indicates whether the first entry should be the arc frame.

```

```

277             (Defaults to True)
278
279         Returns
280         -----
281         None
282
283         """
284         if arc:
285             self.o_files.insert(0, o_name)
286             self.e_files.insert(0, e_name)
287         else:
288             self.o_files.append(o_name)
289             self.e_files.append(e_name)
290
291     return
292
293 # MARK: Save beam lists
294 def save_beam_lists(self, file_suffix: str = 'frames') -> None:
295     with open(f"o_{file_suffix}", "w+") as f_o, \
296         open(f"e_{file_suffix}", "w+") as f_e:
297         for i, j in zip(self.o_files, self.e_files):
298             f_o.write(i + "\n")
299             f_e.write(j + "\n")
300
301     return
302
303 # MARK: Process all Listed Images
304 def process(self) -> None:
305     """
306         Process all FITS images stored in the `fits_list` attribute
307
308     Returns
309     -----
310     None
311
312     """
313     for target in self.fits_list:
314         logging.debug(f"Processing {target}")
315         self.split_file(target)
316
317     self.save_beam_lists()
318
319     return
320
321 # MARK: Main function
322 def main(argv) -> None:
323     """Main function."""
324
325     return
326
327
328 if __name__ == "__main__":
329     main(sys.argv[1:])

```

Listing II.3: The source code for `join.py`

```

1 """Module for joining the split FITS files with an external wavelength
2     solution."""
3
4 #!/usr/bin/env python3
5 # -*- coding: utf-8 -*-
6
7 from __init__ import __author__, __email__, __version__
8
9 # MARK: Imports
10 import os
11 import sys
12 import logging
13 import re
14 from pathlib import Path
15
16 import numpy as np
17 from numpy.polynomial.chebyshev import chebgrid2d as chebgrid2d
18 from numpy.polynomial.legendre import leggrid2d as leggrid2d
19 from astropy.io import fits as pyfits
20
21 # from lacosmic import lacosmic # Replaced: ccdproc is ~6x faster
22 from ccdproc import cosmicray_lacosmic as lacosmic
23
24 from utils.specpolpy3 import read_wollaston, split_sci
25 from utils.SharedUtils import find_files, find_arc
26 from utils.Constants import DATADIR, SAVE_PREFIX, SPLIT_ROW, CR_PARAMS
27
28 # MARK: Join Class
29 class Join:
30
31     #-----join0-----
32
33     """
34     The `Join` class allows for the joining of previously
35     split files and the appending of an external wavelength
36     solution to the `polsalt` FITS file format.
37
38     Parameters
39     -----
40     data_dir : str
41         The path to the data to be joined
42     database : str, optional
43         The name of the `IRAF` database folder.
44         (The default is "database")
45     fits_list : list[str], optional
46         A list of pre-reduced `polsalt` FITS files to be joined within `data_dir`.
47         (The default is ``None``, `Join` will search for `mxbp*.fits` files)
48     solutions_list: list[str], optional
49         A list of solution filenames from which the wavelength solution
50         is created.
51         (The default is ``None``, `Join` will search for `fc*` files
52         within the `database` directory)
53     split_row : int, optional

```

```

52     The row along which the data of each extension in the FITS file
53     ↪ was split.
54     Necessary when Joining cropped files.
55     (The default is 517, the SALT RSS CCD's middle row)
56     save_prefix : dict[str, list[str]], optional
57     The prefix with which the previously split `O`- & `E`-beams
58     ↪ were saved.
59     Used for detecting if cropping was applied during the splitting
60     ↪ procedure.
61     (The default is SAVE_PREFIX (See Notes))
62     verbose : int, optional
63     The level of verbosity to use for the Cosmic ray rejection
64     (The default is 30, I.E. logging.INFO)
65
66     Attributes
67     -----
68     fc_files : list[str]
69     Valid solutions found from `solutions_list`.
70     custom : bool
71     Internal flag for whether `solutions_list` uses the `IRAF` or a
72     ↪ custom format.
73     See Notes for custom solution formatting.
74     (Default (inherited from `solutions_list`) is False)
75     arc : str
76     Deprecated. Name of arc FITS file within `data_dir`.
77     data_dir
78     database
79     fits_list
80     Methods
81     -----
82     get_solutions(wavlist: list / None, prefix: str = "fc")
83     -> (fc_files, custom): tuple[list[str], bool]
84     Parse `solutions_list` and return valid solution files and if
85     ↪ they are non-`IRAF` solutions.
86     parse_solution(fc_file: str, xshape: int, yshape: int)
87     -> tuple[dict[str, int], np.ndarray]
88     Loads the wavelength solution file and parses keywords
89     ↪ necessary for creating the wavelength extension.
90     join_file(file: os.PathLike)
91     -> None
92     Joins the files,
93     attaches the wavelength solutions,
94     performs cosmic ray cleaning,
95     masks the extension,
96     and checks cropping performed in `Split`.
97     Writes the FITS file in a `polsalt` valid format.
98     check_crop(hdu: pyfits.HDUList, o_file: str, e_file: str)
99     -> int
100    Opens the split `O`- and `E`-beam FITS files and returns the
101    ↪ amount of cropping that was performed.
102    process()
103    -> None
104    Calls `join_file` on each file in `fits_list` for automation.

```

```

103
104     Other Parameters
105     -----
106     no_arc : bool, optional
107         Deprecated. Decides whether the arc frames should be processed.
108         (The default is False, `polsalt` has no use for the arc after
109         ↪ wavelength calibrations)
110     **kwargs : dict
111         keyword arguments. Allows for passing unpacked dictionary to
112         ↪ the class constructor.
113
114     Notes
115     -----
116     Constants Imported (See utils.Constants):
117         DATADIR
118         SAVE_PREFIX
119         SPLIT_ROW
120         CR_PARAMS
121
122     Custom wavelength solutions must be formatted as:
123         `x`,
124         `y`,
125         *coefficients...
126     where the solutions are of order (`x` by `y`) and contain  $x*y$ 
127     ↪ coefficients.
128     The name of the custom wavelength solution file must contain either
129     ↪ "cheb" or "leg"
130     for Chebychev or Legendre wavelength solutions, respectively.
131
132     Cosmic ray rejection is performed using lacosmic [1]_
133     ↪ in ccdproc via astroscrappy [2]_.
134
135     References
136     -----
137     .. [1] van Dokkum 2001, PASP, 113, 789, 1420 (article :
138         ↪ http://adsabs.harvard.edu/abs/2001PASP..113.1420V)
139     .. [2] https://zenodo.org/records/1482019
140
141     """
142
143     # -----join1-----
144
145     # MARK: Join init
146     def __init__(
147         self,
148         data_dir: Path,
149         database: str = "database",
150         fits_list: list[str] = None,
151         solutions_list: list[Path] = None,
152         split_row: int = SPLIT_ROW,
153         no_arc: bool = True,
154         save_prefix: Path | None = None,
155         verbose: int = 30,
156         **kwargs,
157     ) -> None:
158         self.data_dir = data_dir
159         self.database = Path(data_dir) / database
160         self.fits_list = find_files(

```

```

155         data_dir=self.data_dir,
156         filenames=fits_list,
157         prefix="mxgbp",
158         ext="fits",
159     )
160     self.fc_files, self.custom = self.get_solutions(solutions_list)
161     self.split_row = split_row
162     self.save_prefix = SAVE_PREFIX
163     if type(save_prefix) == dict:
164         self.save_prefix = save_prefix
165
166     self.no_arc = no_arc
167     self.arc = find_arc(self.fits_list)
168
169     self.verbose = verbose < 30
170
171     logging.debug("__init__ - \n", self.__dict__)
172     return
173
174 # MARK: Find 2D WAV Functions
175 def get_solutions(
176     self,
177     wavlist: list[str] | None,
178     prefix: str = "fc"
179 ) -> tuple[list[str], bool]:
180     """
181         Get the list of wavelength solution files.
182
183     Parameters
184     -----
185     wavlist : list[str] / None
186         A list of custom wavelength solutions files.
187         If ``None``, `Join` will search for wavelength solutions in
188         → the `database` directory.
189     prefix : str, optional
190         The prefix of the wavelength solution files.
191         (Defaults to "fc")
192
193     Returns
194     -----
195     tuple[list[str], bool]
196         A tuple containing the list of wavelength solutions files
197         → and
198         a boolean indicating whether custom solutions were provided.
199
200     """
201     # No custom solutions
202     if not wavlist:
203         # Handle finding solutions
204         ws = []
205         for fl in os.listdir(self.database):
206             if os.path.isfile(self.database / fl) and (prefix ==
207                 fl[0:len(prefix)]):
208                 ws.append(fl)
209
210         if len(ws) != 2:
211             # Handle incorrect number of solutions found
212             msg = (

```

```

210             f"\"Incorrect amount of wavelength solutions \""
211             f"\"{len(ws)} fc... files) found in the solution \""
212             f"\"dir.: {self.database}\""
213         )
214         logging.error(msg)
215         raise FileNotFoundError(msg)
216
217     return (sorted(ws, reverse=True), False)
218
219     # Custom solution
220     if len(wavlist) >= 2:
221         if len(wavlist) > 2:
222             logging.warning(f" Too many solutions, only
223                             ↪ {wavlist[:2]} are considered")
224             wavlist = wavlist[:2]
225
226         for fl in wavlist:
227             if not os.path.isfile(os.path.join(self.data_dir, fl)):
228                 msg = (
229                     f"{fl} not found in the "
230                     f"data directory {self.data_dir}"
231                 )
232                 logging.error(msg)
233                 raise FileNotFoundError(msg)
234
235     return (sorted(wavlist, reverse=True), True)
236
237     # MARK: Parse 2D WAV Function
238     def parse_solution(
239         self,
240         fc_file: str,
241         xshape: int,
242         yshape: int
243     ) -> tuple[dict[str, int], np.ndarray]:
244         """
245             Parse the 2D wavelength solution function from `fc_file`.
246
247             Parameters
248             -----
249             fc_file : str
250                 The filename of the wavelength solutions file.
251             xshape : int
252                 The x-order of the 2D solution.
253             yshape : int
254                 The y-order of the 2D solution.
255
256             Returns
257             -----
258             tuple[dict[str, int], np.ndarray]
259                 A tuple containing a dictionary of the parameters of the
260                             ↪ solution function
261                             and the function coefficients.
262
263             """
264             fit_params = {}
265             coeff = []
266
267             if self.custom:

```

```

266     # Load coefficients
267     coeff = np.loadtxt(fc_file)
268
269     fit_params["xorder"] = coeff[0].astype(int)
270     fit_params["yorder"] = coeff[1].astype(int)
271     coeff = coeff[2:]
272
273     f_type = 3
274     if "cheb" in str(fc_file): f_type = 1
275     elif "leg" in str(fc_file): f_type = 2
276     fit_params["function"] = f_type
277
278     fit_params["xmin"], fit_params["xmax"] = 1, xshape
279     fit_params["ymin"], fit_params["ymax"] = 1, yshape
280
281 else:
282     # Parse IRAF fc database files
283     file_contents = []
284     with open(self.database / fc_file) as fcfile:
285         for i in fcfile:
286             file_contents.append(re.sub(r"\n\t\s*", "", i))
287
288     if file_contents[9] != "1.": # xterms - Cross-term type
289         msg = (
290             "Cross-term not recognised (always 1 for "
291             "'FITCOORDS'), redo FITCOORDS or change manually."
292         )
293         raise Exception(msg)
294
295     fit_params["function"] = int(file_contents[6][-1])
296
297     fit_params["xorder"] = int(file_contents[7][-1])
298     fit_params["yorder"] = int(file_contents[8][-1])
299
300     fit_params["xmin"] = int(file_contents[10][-1])
301     fit_params["xmax"] = xshape
302     # int(file_contents[11][-1])# stretch fit over x
303     fit_params["ymin"] = int(file_contents[12][-1])
304     fit_params["ymax"] = yshape
305     # int(file_contents[13][-1])# stretch fit over y
306
307     coeff = np.array(file_contents[14:], dtype=float)
308
309     coeff = np.reshape(
310         coeff,
311         (fit_params["xorder"], fit_params["yorder"]))
312
313
314     return (fit_params, coeff)
315
316 # MARK: Join Files
317 def join_file(self, file: os.PathLike) -> None:
318     """
319     Join the `O`- and `E`-beams, attach the wavelength solutions,
320     perform cosmic ray cleaning, mask the extensions,
321     and checks cropping performed by `Split`.
322     Write the FITS file in a `polsalt` valid format.
323

```

```

324     Parameters
325     -----
326     file : os.PathLike
327         The path of the FITS file to be joined.
328
329     See Also
330     -----
331     IRAF - `fitcoords` task
332         https://iraf.net/irafdocs/formats/fitcoords.php,
333         numpy 2D grid functions
334             https://numpy.org/doc/stable/reference/generated/numpy
335             Chebyshev: + '.polynomial.chebyshev.chebgrid2d.html'">''.polynomial.chebyshev.chebgrid2d.html'
336             Legendre: + '.polynomial.legendre.leggrid2d.html'">''.polynomial.legendre.leggrid2d.html'
337
338     """
339     # Create empty wavelength appended hdu list
340     whdu = pyfits.HDUList()
341     primary_ext = ""
342
343     # Handle prefix and names
344     pref = "arc" if file == self.arc else "beam"
345     o_file = self.save_prefix[pref][0] + file.name[-9:]
346     e_file = self.save_prefix[pref][1] + file.name[-9:]
347
348     # Open file
349     with pyfits.open(file) as hdu:
350         # Check if file has been cropped
351         cropsize = self.check_crop(hdu, o_file, e_file)
352
353         y_shape = int(hdu["SCI"].data.shape[0] / 2) - cropsize
354         x_shape = hdu["SCI"].data.shape[1]
355
356         # No differences in "PRIMARY" extention header
357         primary_ext = hdu["PRIMARY"]
358         whdu.append(primary_ext)
359
360         for ext in ["SCI", "VAR", "BPM"]:
361             whdu.append(pyfits.ImageHDU(name=ext))
362             whdu[ext].header = hdu[ext].header.copy()
363             whdu[ext].header["CTYPE3"] = "O,E"
364
365             # Create empty extention with correct order and format
366             if ext == "BPM":
367                 whdu[ext].data = np.zeros(
368                     (2, y_shape, x_shape),
369                     dtype="uint8")
370
371                 whdu[ext].header["BITPIX"] = "-uint8"
372             else:
373                 whdu[ext].data = np.zeros(
374                     (2, y_shape, x_shape),
375                     dtype=">f4")
376
377                 whdu[ext].header["BITPIX"] = "-32"
378
379             # Fill in empty extentions
380             if cropsize:
381                 temp_split = split_sci(

```

```

382             hdu ,
383             self.split_row ,
384             ext=ext
385         )[ext].data
386         whdu[ext].data[0] = temp_split[0, cropsize:]
387         whdu[ext].data[1] = temp_split[1, 0:-cropsize]
388
389     else:
390         whdu[ext].data = split_sci(
391             hdu ,
392             self.split_row ,
393             ext=ext
394         )[ext].data
395     # End of hdu calls, close hdu
396
397     # MARK: Join (Wav. Ext.)
398     whdu.append(pyfits.ImageHDU(name="WAV"))
399     wav_header = whdu["SCI"].header.copy()
400     wav_header["EXTNAME"] = "WAV"
401     wav_header["CTYPE3"] = "O,E"
402     whdu["WAV"].header = wav_header
403
404     whdu["WAV"].data = np.zeros(
405         whdu["SCI"].data.shape ,
406         dtype='>f4'
407     )
408
409     for num, fname in enumerate(self.fc_files):
410         pars, chebvals = self.parse_solution(
411             fname ,
412             x_shape ,
413             y_shape
414         )
415
416         if pars["function"] == 1: # Function type (1 = chebyshev)
417             # Set wavelength extention values to function
418             whdu["WAV"].data[num] = chebgrid2d(
419                 x=np.linspace(-1, 1, pars["ymax"]),
420                 y=np.linspace(-1, 1, pars["xmax"]),
421                 c=chebvals,
422             )
423
424         elif pars["function"] == 2: # Function type (2 = legendre)
425             # Set wavelength extention values to function
426             whdu["WAV"].data[num] = leggrid2d(
427                 x=np.linspace(-1, 1, pars["ymax"]),
428                 y=np.linspace(-1, 1, pars["xmax"]),
429                 c=chebvals,
430             )
431
432     else:
433         msg = (
434             "Function type not recognised, please wavelength "
435             "calibrate using either chebychev or legendre."
436         )
437         raise Exception(msg)
438
439     # MARK: Cosmic Ray Cleaning

```

```

440     # See utils.Constants for `CR_PARAMS` discussion
441     whdu["SCI"].data[num] = lacosmic(
442         whdu["SCI"].data[num],
443         # contrast=CR_PARAMS['CR_CONTRAST'],
444         # threshold=CR_PARAMS['CR_THRESHOLD'],
445         # neighbor_threshold=CR_PARAMS['CR_NEIGH_THRESH'],
446         # effective_gain=CR_PARAMS['GAIN'],
447         # background=CR_PARAMS['BACKGROUND'],
448         readnoise=CR_PARAMS['READNOISE'],
449         gain=CR_PARAMS['GAIN'],
450         verbose=self.verbose,
451     )[0]
452
453     # MARK: WAV masking
454     # Left & Right Crop
455     whdu["WAV"].data[whdu["WAV"].data[:] < 3_000] = 0.0
456     whdu["WAV"].data[whdu["WAV"].data[:] >= 10_000] = 0.0
457
458     # Top & Bottom Crop (shift\tilt)
459     rpix_oc, cols, rbin, lam_c = read_wollaston(
460         whdu,
461         DATADIR + "wollaston.txt"
462     )
463
464     drow_oc = (rpix_oc - rpix_oc[:, int(cols / 2)][:, None]) / rbin
465
466     ## Cropping as suggested
467     for c, col in enumerate(drow_oc[0]):
468         if np.isnan(col):
469             continue
470
471         if int(col) < 0:
472             whdu["WAV"].data[0, int(col) :, c] = 0.0
473         elif int(col) > cropsize:
474             whdu["WAV"].data[0, 0 : int(col) - cropsize, c] = 0.0
475
476     for c, col in enumerate(drow_oc[1]):
477         if np.isnan(col):
478             continue
479
480         if int(col) > 0:
481             whdu["WAV"].data[1, 0 : int(col), c] = 0.0
482         elif (int(col) < 0) & (abs(int(col)) > cropsize):
483             whdu["WAV"].data[1, int(col) + cropsize :, c] = 0.0
484
485     # MARK: BPM masking
486     whdu["BPM"].data[0] = np.where(
487         whdu["WAV"].data[0] == 0,
488         1,
489         whdu["BPM"].data[0]
490     )
491     whdu["BPM"].data[1] = np.where(
492         whdu["WAV"].data[1] == 0,
493         1,
494         whdu["BPM"].data[1]
495     )
496
497     whdu.writeto(f"w{os.path.basename(file)}", overwrite="True")

```

```

498     return
499
500
501 # MARK: Check Crop
502 def check_crop(
503     self,
504     hdu: pyfits.HDUList,
505     o_file: str,
506     e_file: str
507 ) -> int:
508     """
509         Check if cropping is necessary when joining `O`- and `E`-beams.
510
511     Parameters
512     -----
513     hdu : astropy.io.fits.HDUList
514         The HDUList to check for cropping.
515     o_file : str
516         The name of the previously split `O`-beam FITS file.
517     e_file : str
518         The name of the previously split `E`-beam FITS file.
519
520     Returns
521     -----
522     int
523         The number of rows which were cropped by `Split`.
524
525     """
526     cropsize = 0
527     o_y = 0
528     e_y = 0
529
530     with pyfits.open(o_file) as o, \
531         pyfits.open(e_file) as e:
532         o_y = o[0].data.shape[0]
533         e_y = e[0].data.shape[0]
534
535     if hdu["SCI"].data.shape[0] != (o_y + e_y):
536         # Get crop size, assuming crop same on both sides
537         cropsize = int((hdu["SCI"].data.shape[0] - o_y - e_y) / 2)
538
539     return cropsize
540
541 # MARK: Process all Listed Images
542 def process(self) -> None:
543     """Process all FITS images stored in the `fits_list`  

544     ↳ attribute"""
545     for target in self.fits_list:
546         logging.debug(f"Processing {target}")
547         self.join_file(target)
548
549
550
551 def main(argv) -> None:
552     """Main function."""
553
554     return

```

```
555
556
557 if __name__ == "__main__":
558     main(sys.argv[1:])
```

Listing II.4: The source code for `cross_correlate.py`

```

1 """Module for cross correlating polarization beams."""
2
3 #!/usr/bin/env python3
4 # -*- coding: utf-8 -*-
5
6 from __init__ import __author__, __email__, __version__
7
8 # MARK: Imports
9 import os
10 import sys
11 import logging
12 import itertools as iters
13 from pathlib import Path
14 from typing import Callable
15
16 import numpy as np
17 from numpy.polynomial import chebyshev
18 import matplotlib.pyplot as plt
19 from astropy.io import fits as pyfits
20 from scipy import signal
21
22 from utils.SharedUtils import find_files, continuum
23 from utils.Constants import SAVE_CORR
24
25 OFFSET = 0.3
26
27 mpl_logger = logging.getLogger('matplotlib')
28 mpl_logger.setLevel(logging.INFO)
29
30 # MARK: Correlate class
31 class CrossCorrelate:
32
33     #-----corr0-----
34
35     """
36         Cross correlate allows for comparing the extensions of multiple
37         FITS files, or comparing the O and E beams of a single FITS file.
38
39     Parameters
40     -----
41     data_dir : str
42         The path to the data to be cross correlated
43     filenames : list[str]
44         The ecwmxgbp*.fits files to be cross correlated.
45         If only one filename is defined, correlation is done against
46         ↪ the two polarization beams.
47     split_ccd : bool, optional
48         Decides whether the CCD regions should each be individually
49         ↪ cross correlated.
50         (The default is True, which splits the spectrum up into its
51         ↪ separate CCD regions)
52     cont_ord : int, optional
53         The degree of a chebyshev to fit to the continuum.
54         (The default is 11)
55     plot : bool, optional
56         Decides whether or not the continuum fitting should be plotted

```

```

54     (The default is False, so no continua plots are displayed)
55 save_prefix : str, optional
56     The name or directory to save the figure produced to.
57     "." saves a default name to the current working. A default name
58     ↪ is also used when save_prefix is a directory.
59     (The default is None, I.E. The figure is not saved, only
60     ↪ displayed)

61 Attributes
62 -----
63 data_dir
64 fits_list
65 beams : str
66     The mode of correlation.
67     'OE' for same file, and 'O' or 'E' for different files but same
68     ↪ ext's.
69 ccds : int
70     The number of CCD's in the data. Used to split the CCD's if
71     ↪ split_ccd is True.
72 cont_ord : int
73     The degree of the chebyshev to fit to the continuum.
74 can_plot : bool
75     Decides whether or not the continuum fitting should be plotted
76 offset : int
77     The amount the spectrum is shifted, mainly to test the effect
78     ↪ of the cross correlation
79     (The default is 0, I.E. no offset introduced)
80 save_prefix
81 wav_unit : str
82     The units of the wavelength axis.
83     (The default is Angstroms)
84 wav_cdelt : int
85     The wavelength increment.
86     (The default is 1)
87 alt : Callable
88     An alternate method of cross correlating the data.
89     (The default is None)

90 Methods
91 -----
92 load_file(filename: Path)
93     -> tuple[np.ndarray, np.ndarray, np.ndarray]
94     Loads the data from a FITS file.
95 get_bounds(bpm: np.ndarray)
96     -> np.ndarray
97     Finds the bounds for the CCD regions.
98 remove_cont(spec: list, wav: list, bpm: list, plotCont: bool)
99     -> None
100    Removes the continuum from the data.
101 correlate(filename1: Path, filename2: Path / None = None)
102    -> None
103    Cross correlates the data.
104 FTCS(filename1: Path, filename2: Path / None = None)
105    -> None
106    Cross correlates the data using the Fourier Transform.
107 plot(spec, wav, bpm, corrrdb, lagsdb)
108    -> None
109    Plots the data.
110

```

```

107     process()
108         -> None
109         Processes the data.
110
111     Other Parameters
112     -----
113     offset : int, optional
114         The amount the spectrum is shifted, mainly to test the effect
115         ↵ of the cross correlation
116         (The default is 0, I.E. no offset introduced)
117     **kwargs : dict
118         keyword arguments. Allows for passing unpacked dictionary to
119         ↵ the class constructor.
120     FTCS : bool, optional
121         Decides whether the Fourier Transform should be used for
122         ↵ cross correlation.
123
124     See Also
125     -----
126     scipy
127         https://docs.scipy.org/doc/scipy/reference/generated/
128         correlation: scipy.signal.correlate.html
129
130     Notes
131     -----
132     Constants Imported (See utils.Constants):
133         SAVE_CORR
134
135     #-----corr1-----
136
137     # MARK: Correlate init
138     def __init__(self,
139         data_dir: Path,
140         filenames: list[str],
141         beams: str = "OE",
142         split_ccd: bool = True,
143         cont_ord: int = 11,
144         plot: bool = False,
145         offset: int = 0,
146         save_prefix: Path | None = None,
147         **kwargs
148     ) -> None:
149         self.data_dir = data_dir
150         self.fits_list = find_files(
151             data_dir=self.data_dir,
152             filenames=filenames,
153             prefix="ecwmxgbp",
154             ext="fits",
155         )
156         self._beams = None
157         self.beams = beams
158         self.ccds = 1
159         if split_ccd:
160             # BPM == 2 near center of CCD if CCD count varies

```

```

162         with pyfits.open(self.fits_list[0]) as hdu:
163             self.ccds = sum(hdu["BPM"].data.sum(axis=1)[0] == 2)
164
165             self.cont_ord = cont_ord
166             self.can_plot = plot
167             self.offset = offset
168             if offset != 0:
169                 logging.warning("'offset' is only for testing.")
170                 # Add an offset to the spectra to test cross correlation
171                 # self.spec1 = np.insert(
172                 #     self.spec1, [0] * offset, self.spec1[:, :offset],
173                 #     axis=-1
174                 # )[ :, : self.spec1.shape[-1]]
175
176             self.save_prefix = save_prefix
177             # Handle directory save name
178             if self.save_prefix and self.save_prefix.is_dir():
179                 self.save_prefix /= SAVE_CORR
180                 logging.warning((
181                     f"Correlation save name resolves to a directory. "
182                     f"Saving under {self.save_prefix}"
183                 ))
184
185             self.wav_unit = "$\AA$"
186             self.wav_cdelt = 1
187
188             self.alt = self.FTCS if kwargs.get("FTCS") else None
189
190             logging.debug("__init__ - \n", self.__dict__)
191             return
192
193             # MARK: Beams property
194             @property
195             def beams(self) -> str:
196                 return self._beams
197
198             @beams.setter
199             def beams(self, mode: str) -> None:
200                 if mode not in ['O', 'E', 'OE']:
201                     errMsg = f"Correlation mode '{mode}' not recognized."
202                     logging.error(errMsg)
203                     raise ValueError(errMsg)
204
205                 self._beams = mode
206
207             return
208
209             # MARK: Load file
210             def load_file(
211                 self,
212                 filename: Path
213             ) -> tuple[np.ndarray, np.ndarray, np.ndarray]:
214                 """
215
216                 Load the data from a FITS file.
217
218                 Parameters
219                 -----
220                 filename : Path

```

```

219     The name of the FITS file to load.
220
221     Returns
222     -----
223     tuple[np.ndarray, np.ndarray, np.ndarray]
224         The spectrum, wavelength, and bad pixel mask.
225
226     """
227     spec, wav, bpm = None, None, None
228
229     # Open HDU
230     with pyfits.open(filename) as hdul:
231         spec = hdul["SCI"].data.sum(axis=1)
232         wav = (
233             np.arange(spec.shape[-1])
234             * hdul["SCI"].header["CDELT1"]
235             + hdul["SCI"].header["CRVAL1"]
236         )
237         wav = np.array((wav, wav))
238         bpm = hdul["BPM"].data.sum(axis=1)
239
240         self.wav_cdel = float(hdul["SCI"].header["CDELT1"])
241
242         if hdul["SCI"].header["CTYPE1"] != 'Angstroms':
243             self.wav_unit = hdul["SCI"].header["CTYPE1"]
244
245     return spec, wav, bpm
246
247     # MARK: Get bounds
248     def get_bounds(self, bpm: np.ndarray) -> np.ndarray:
249         """
250             Find the bounds for a file based on the CCD count.
251
252             Parameters
253             -----
254             bpm : np.ndarray
255                 The bad pixel mask.
256
257             Returns
258             -----
259             np.ndarray
260                 The bounds for the CCD regions.
261
262         """
263         # bounds.shape -> (0/E, CCD's, low./up. bound)
264         if self.ccds == 1:
265             return np.array(
266                 [(0, bpm[0].shape[-1]), (0, bpm[1].shape[-1])]
267             ).astype(int)
268
269         bounds = np.zeros((2, self.ccds, 2))
270
271         # Get lower and upper bound for each ccd, save to bounds
272         # Lower -> min is zero, Upper -> max is bpm length
273         for ext, ccd in iters.product(range(2), range(self.ccds)):
274             mid = np.where(bpm[ext] == 2)[0][ccd]
275             CCDs = self.ccds * 2
276             bounds[ext, ccd] = (

```

```

277             max(mid - bpm.shape[-1] // CCDs, 0),
278             min(mid + bpm.shape[-1] // CCDs, bpm.shape[-1])
279         )
280
281     return bounds.astype(int)
282
283 # MARK: Remove Continua
284 def remove_cont(
285     self,
286     spec: list,
287     wav: list,
288     bpm: list,
289     plotCont: bool
290 ) -> None:
291     """
292         Remove the continuum from the data.
293
294     Parameters
295     -----
296     spec : list
297         The spectrum to remove the continuum from.
298     wav : list
299         The wavelength of the spectrum.
300     bpm : list
301         The bad pixel mask.
302     plotCont : bool
303         Decides whether or not the continuum fitting should be
304         ↪ plotted
305
306     Returns
307     -----
308     None
309
310     """
311     # Mask out the bad pixels for fitting continua
312     okwav = np.where(bpm != 1)
313
314     # Define continua
315     ctm = continuum(
316         wav[okwav],
317         spec[okwav],
318         deg=self.cont_ord,
319         plot=plotCont,
320     )
321
322     # Normalise spectra
323     spec /= chebyshev.chebval(wav, ctm)
324     spec -= 1
325
326     return spec
327
328 # MARK: Correlate
329 def correlate(
330     self,
331     filename1: Path,
332     filename2: Path | None = None,
333     alt: Callable = None
334 ) -> None:

```

```

334     """
335     Cross correlates the data.
336
337     Parameters
338     -----
339     filename1 : Path
340         The name of the first FITS file to cross correlate.
341     filename2 : Path, optional
342         The name of the second FITS file to cross correlate.
343         (Defaults to None)
344     alt : Callable, optional
345         An alternate method of cross correlating the data.
346         (Defaults to None)
347
348     Returns
349     -----
350     None
351
352     """
353     # mode: 0E -> '01' & 'E1', 0 -> '01' & '02', E -> 'E1' & 'E2'
354     # Load data
355     spec, wav, bpm = self.load_file(filename1)
356     if filename2 and self.beams != '0E':
357         unpack = lambda ext, *args: [arr[ext] for arr in args]
358
359         if self.beams == '0':
360             spec[-1], wav[-1], bpm[-1] = unpack(
361                 0, *self.load_file(filename2))
362         )
363
364     else:
365         spec[0], wav[0], bpm[0] = spec[-1], wav[-1], bpm[-1]
366         spec[-1], wav[-1], bpm[-1] = unpack(
367             -1, *self.load_file(filename2))
368         )
369
370     bounds = self.get_bounds(bpm)
371
372     logging.debug(
373         f"correlate - data shape:\n\tspec/wav/bpm: {spec.shape}"
374     )
375
376     corrdb = [[] for _ in range(self.ccdb)]
377     lagsdb = [[] for _ in range(self.ccdb)]
378     for ccd in range(self.ccdb):
379         sig = []
380         for ext in range(2):
381             lb, ub = bounds[ext, ccd]
382
383             if self.cont_ord > 0:
384                 spec[ext, lb:ub] = self.remove_cont(
385                     spec[ext, lb:ub],
386                     wav[ext, lb:ub],
387                     bpm[ext, lb:ub],
388                     self.can_plot
389                 )
390
391             # Invert BPM (and account for 2); zero bad pixels

```

```

392         sig.append((
393             spec[ext, lb:ub]
394             * abs(bpm[ext, lb:ub] * -1 + 1)
395         ))
396
397     # Finally(!!!) cross correlate signals and scale max -> 1
398     corrdb[ccd] = signal.correlate(*sig) if not alt else
399     ↪ alt(*sig)
400     corrdb[ccd] /= np.max(corrdb[ccd])
401     lagsdb[ccd] = signal.correlation_lags(
402         sig[0].shape[-1],
403         sig[1].shape[-1]
404     ) * self.wav_cdel
405
406     return (spec, wav, bpm), (corrdb, lagsdb)
407
408 # MARK: FTCS alternate
409 def FTCS(
410     self,
411     signal1: np.ndarray,
412     signal2: np.ndarray
413 ) -> None:
414     """
415     Cross correlates the data using the Fourier Transform.
416
417     Parameters
418     -----
419     signal1 : np.ndarray
420         The first signal to cross correlate.
421     signal2 : np.ndarray
422         The second signal to cross correlate.
423
424     Returns
425     -----
426     np.ndarray
427         The correlation data using the Fourier Transform.
428
429     """
430     logging.debug(
431         f"FTCS - data shape:\n{tspec/wav/bpm: {signal1.shape}}"
432     )
433
434     # Invert BPM (and account for 2); zero bad pixels
435     ft_spec1 = np.fft.fft(signal1)
436     ft_spec2 = np.fft.fft(signal2)
437
438     if self.can_plot:
439         plt.plot(ft_spec1)
440         plt.plot(ft_spec2)
441         plt.show()
442
443     # Cross correlate signals
444     # ft_spectrum1 * np.conj(ft_spectrum2)
445     corr_entry = signal.correlate(ft_spec1, ft_spec2)
446
447     return np.fft.ifft(corr_entry)
448
449 # MARK: Plot

```

```

449     def plot(self, spec, wav, bpm, corrdb, lagsdb) -> None:
450         """
451             Plot the data.
452
453             Parameters
454             -----
455             spec : np.ndarray
456                 The spectrum.
457             wav : np.ndarray
458                 The wavelength.
459             bpm : np.ndarray
460                 The bad pixel mask.
461             corrdb : np.ndarray
462                 The cross correlation data.
463             lagsdb : np.ndarray
464                 The lags data.
465
466             Returns
467             -----
468             None
469
470             """
471     plt.style.use(Path(__file__).parent.resolve() /
472                   'utils/STOPS.mplstyle')
472     bounds = self.get_bounds(bpm)
473
474     fig, axs = plt.subplots(2, self.ccds, sharey="row")
475
476     if self.ccds == 1:
477         # Convert axes to a 2D array
478         axs = np.swapaxes(np.atleast_2d(axs), 0, 1)
479
480     # for ext, ccd in iters.product(range(2), range(self.ccds)):
481
482         for ccd in range(self.ccds):
483             axs[0, ccd].plot(
484                 lagsdb[ccd],
485                 corrdb[ccd] * 100,
486                 color='C4',
487                 label=f"max lag @ {lagsdb[ccd][corrdb[ccd].argmax()]} - "
488                       f"(bounds[1, ccd, 0] - bounds[0, ccd, 0])",
489             )
490
491         for ext in range(2):
492             lb, ub = bounds[ext, ccd]
493             logging.debug(f"fl-{ext}: {wav[ext, lb]}:{wav[ext, ub - "
494                           f"1]}")
495
496             axs[1, ccd].plot(
497                 wav[ext, lb:ub],
498                 spec[ext, lb:ub] * abs(bpm[ext, lb:ub] * -1 + 1) +
499                 OFFSET * ext,
500                 label=
501                     f"${self.beams if self.beams != 'OE' else "
502                      f"self.beams[{ext}]}"
503                     f"_{{ext + 1 if self.beams != 'OE' else 1}}$"
504                     f"{{{('+' + str(OFFSET * ext)) + ')')}} if ext > 0 "
505                         f"else ''}"

```

```

501             ),
502         )
503
504     axs[0, 0].set_ylabel("Normalised Correlation\n(\%)")
505     for ax in axs[0, :]:
506         ax.set_xlabel("Signal Lag")
507     for ax in axs[1:, 0]:
508         ax.set_ylabel(f"Norm. Intensity\n(Counts)")
509     for ax in axs[-1, :]:
510         ax.set_xlabel(f"Wavelength ({self.wav_unit})")
511     for ax in axs.flatten():
512         ax.legend()
513
514     # plt.tight_layout()
515     # fig1 = plt.gcf()
516     # DPI = fig1.get_dpi()
517     # fig1.set_size_inches(700.0/float(DPI), 250.0/float(DPI))
518     plt.show()
519
520     # Handle do not save
521     if not self.save_prefix:
522         return
523
524     # Handle save
525     fig.savefig(fname=self.save_prefix)
526
527     return
528
529     # MARK: Process all listed images
530 def process(self) -> None:
531     """
532     Process the data.
533
534     Returns
535     -----
536     None
537
538     """
539     if self.beams != 'OE' and len(self.fits_list) == 1:
540         # change mode to OE with warning
541         logging.warning((
542             f"`{self.beams}` correlation not possible for "
543             "a single file. correlation `mode` changed to 'OE'."
544         ))
545         self.beams = 'OE'
546
547     # OE `mode` (same file, diff. ext.)
548     if self.beams == 'OE':
549         for fl in self.fits_list:
550             logging.info(f'"OE' correlation of {fl}.')
551             (spec, wav, bpm), (corr, lags) = self.correlate(fl,
552                 ↪ alt=self.alt)
553             self.plot(spec, wav, bpm, corr, lags)
554
555     return
556
557     # O/E `mode` (diff. files, same ext.)
558     for fl1, fl2 in iters.combinations(self.fits_list, 2):

```

```
558     logging.info(f"{{self.beams}} correlation of {f11} vs {f12}.")  
559     (spec, wav, bpm), (corr, lags) = self.correlate(f11, f12,  
560      ↪ alt=self.alt)  
561     self.plot(spec, wav, bpm, corr, lags)  
562  
563  
564  
565 # MARK: Main function  
566 def main(argv) -> None:  
567     return  
568  
569 if __name__ == "__main__":  
570     main(sys.argv[1:])
```

Listing II.5: The source code for `skylines.py`

```

1 """Module for analyzing the sky lines of a wavelength calibrated
2    ↪ image."""
3
4 #!/usr/bin/env python3
5 # -*- coding: utf-8 -*-
6
7 from __init__ import __author__, __email__, __version__
8
9 # MARK: Imports
10 import os
11 import sys
12 import logging
13 from pathlib import Path
14
15 import numpy as np
16 import matplotlib.pyplot as plt
17 from astropy.io import fits as pyfits
18 from scipy import signal, stats, interpolate
19
20 from utils.SharedUtils import find_files, continuum
21 from utils.Constants import SAVE_SKY
22
23 mpl_logger = logging.getLogger('matplotlib')
24 mpl_logger.setLevel(logging.INFO)
25 # plt.rcParams['figure.figsize'] = (20, 4)
26
27 # MARK: Skylines Class
28 class Skylines:
29
30     #-----sky0-----
31
32     """
33         Class representing the Skylines object.
34
35     Parameters
36     -----
37     data_dir : Path
38         The directory containing the data files.
39     filenames : list[str]
40         The list of filenames to be processed.
41     beam : str, optional
42         The beam mode, by default "OE".
43     plot : bool, optional
44         Flag indicating whether to plot the continuum, by default False.
45     save_prefix : Path / None, optional
46         The prefix for saving the data, by default None.
47     **kwargs
48         Additional keyword arguments.
49
50     Attributes
51     -----
52     data_dir : Path
53         The directory containing the data files.
54     fits_list : list[str]
55         The list of fits file paths.
      beam : str

```

```

56     The beam mode.
57     can_plot : bool
58         Flag indicating whether to plot the continuum.
59     save_prefix : Path | None
60         The prefix for saving the data.
61     wav_unit : str
62         The unit of wavelength.
63     rawWav : np.ndarray
64         The raw wavelength data.
65     rawSpec : np.ndarray
66         The raw spectral data.
67     rawBpm : np.ndarray
68         The raw bad pixel mask data.
69     corrWav : np.ndarray
70         The corrected wavelength data.
71     corrSpec : np.ndarray
72         The corrected spectral data.
73     spec : np.ndarray
74         The median spectrum.
75     normSpec : np.ndarray
76         The normalized spectrum.

77
78     Methods
79     -----
80     checkLoad(self, path1: str) -> np.ndarray:
81         Checks and loads the data from the given path.
82     transform(self, wav_sol: np.ndarray, spec: np.ndarray) ->
83         np.ndarray:
84         Transforms the input wavelength and spectral data based on the
85         given wavelength solution.
86     rmvCont(self) -> np.ndarray:
87         Removes the continuum from the spectrum.
88     skylines(self) -> None:
89         Placeholder method for processing skylines.
90     process(self) -> None:
91         Placeholder method for processing the data.
92     """
93
94     # -----sky1-----
95
96     # MARK: Skylines init
97     def __init__(
98         self,
99         data_dir: Path,
100        filenames : list[str],
101        beams: str = "OE",
102        split_ccd: bool = False,
103        cont_ord: int = 11,
104        plot: bool = False,
105        transform: bool = True,
106        save_prefix: Path | None = None,
107        **kwargs,
108    ) -> None:
109        self.data_dir = data_dir
110        self.fits_list = find_files(
111            data_dir=self.data_dir,
112            filenames=filenames,
113            prefix="wmxgbp", # t[o/e]beam

```



```

169     filename : Path / None, optional
170         The path to the file to be loaded.
171         Defaults to loading the skylines from utils/sky.salt
172
173     Returns
174     -----
175     sky_lines : np.ndarray
176         The sky lines from the file.
177
178     """
179     if not filename:
180         filename = Path(__file__).parent.resolve() /
181             'utils/sky.salt'
182
183     dtype = [('wav', float), ('flux', float)]
184     skylines = np.genfromtxt(filename, dtype=dtype, skip_header=3,
185                             skip_footer=1)
186
187     if self.can_plot:
188         plt.plot(skylines['wav'], skylines['flux'], 'x',
189                   label="Model peaks")
190         plt.xlabel(f'Wavelength {self.wav_unit}')
191         plt.ylabel('Relative intensities')
192         plt.title('Known sky lines')
193         plt.legend()
194         plt.show()
195
196     return skylines
197
198 # MARK: Transform spectra
199 @staticmethod
200 def transform(wav_sol: np.ndarray, spec: np.ndarray, resPlot: bool
201               = False) -> np.ndarray:
202     """
203     Transforms the input wavelength and spectral data based on the
204     given wavelength solution.
205
206     Parameters
207     -----
208     wav_sol : np.ndarray
209         The wavelength solution.
210     spec : np.ndarray
211         The spectral data.
212
213     Returns
214     -----
215     wav, spec : np.ndarray
216         The transformed wavelength and spectral data.
217
218     """
219     # Create arrays to return
220     cw = np.zeros_like(wav_sol)
221     cs = np.zeros_like(wav_sol)
222
223     exts = cw.shape[0]
224     rows = cw.shape[1]
225
226     for ext in range(exts):
227

```

```

222     # Get middle row (to interpolate the rest of the rows to)
223     avg_max = [np.where(spec[ext, :, col] == spec[ext, :, 
224         ↪ col].max())[0][0] for col in range(spec[ext].shape[1])]
225     avg_max = np.sum(avg_max) // spec[ext].shape[1]
226
227     # Get wavelength values at row with most trace
228     wav = wav_sol[ext, avg_max, :]
229
230     # Correct extensions based on wavelength
231     cw[ext, :, :] = wav
232
233     # Spec ext
234     # for row in range(rows):
235     #     f_2d = interpolate.interp2d(
236     #         wav_sol[ext, row],
237     #         np.arange(rows),
238     #         spec[ext],
239     #         )
240     #     cs[ext] = f_2d(cw[ext, row], np.arange(rows))
241     for row in range(rows):
242         cs[ext][row, :] = np.interp(
243             wav,
244             wav_sol[ext][row, :],
245             spec[ext][row, :]
246         )
247
248     # Plot results
249     if resPlot:
250         fig, ax1 = plt.subplots(figsize=[20, 4])
251         ax1.imshow(cs[ext],
252                     vmax=cs[0].mean() + 2*cs[0].std(),
253                     vmin=cs[0].mean() - 2*cs[0].std()
254                 )
255         print(f"Average continuum of {'E' if ext else 'O'} at
256             ↪ {np.median(np.median(cs[ext], axis=0)):4.3f}")
257         ax2 = ax1.twinx()
258         ax2.hlines(np.median(np.median(cs[ext], axis=0)), 0,
259             ↪ cs[ext].shape[-1], colors='black')
260         ax2.plot(cs[ext].mean(axis=0), "k", label=f"mean {'E',
261             ↪ if ext else 'O'}")
262         ax2.plot(np.median(cs[ext], axis=0), "r",
263             ↪ label=f"median {'E' if ext else 'O'}")
264         ax2.legend()
265         plt.show()
266
267     return cw, cs
268
269     # MARK: Remove continuum
270     def remove_cont(self, spec: np.ndarray, wav: np.ndarray) ->
271         ↪ np.ndarray:
272         ctm = continuum(wav, spec, deg=self.cont_ord,
273             ↪ plot=self.can_plot)
274
275         return self.spec / ctm - 1
276
277     # MARK: Skyline
278     def skyline(self, filename) -> None:

```

```

# raise error if arc image
with pyfits.open(filename) as hdul:
    if hdul[0].header['OBSTYPE'] == 'ARC':
        logging.warning(f"ARC images, {filename}, contain no
                         sky lines. File skipped.")
        return

    # Load data
    spec2D = hdul["SCI"].data
    wav2D = hdul["WAV"].data
    bpm2D = hdul["BPM"].data

    spec2D *= ~bpm2D

    logging.debug(f"skylines - {filename.name} - spec:
                  {spec2D.shape}")

    # Mask trace
    # TODO@JustinotherGitter: Add trace masking if median is
    # insufficient

    # Save initial feature widths
    # Mean to not filter out skewed features
    spec1D_init = np.mean(spec2D, axis=1)
    # Median to sort for most common wavelength
    wav1D_init = np.median(wav2D, axis=1)

    peaks = [[] for _ in range(2)]
    properties = [[] for _ in range(2)]

if self.can_plot: fig, axs = plt.subplots(2, 1)
for ext in range(2):
    peaks[ext], properties[ext] = signal.find_peaks(
        spec1D_init[ext],
        prominence=0.5 * np.std(spec1D_init[ext]),
        width=[1, 1000],
        rel_height=0.3
    )
    peak_width = [properties[ext]['widths'],
                  properties[ext]['width_heights'],
                  properties[ext]['left_ips'],
                  properties[ext]['right_ips']]

    logging.debug(f"skylines - initial features {'E' if ext
                  else 'O'}: {len(peaks[ext])}")
    logging.debug(f"skylines - props: {properties[ext]}")

if self.can_plot:
    axs[ext].plot(spec1D_init[ext], label=f'{0 if ext
                                              else 1} initial')
    axs[ext].vlines(peaks[ext], 0,
                    np.mean(spec1D_init[ext]), color='r', label='Feature
                    positions')
    axs[ext].hlines(*peak_width[1:], color='g',
                   label='Initial widths')
    axs[ext].errorbar(
        peaks[ext],
        properties[ext]['prominences'],
        yerr=peak_width[0])

```

```

320             xerr=np.array([
321                 peaks[ext] - properties[ext]['left_ips'],
322                 properties[ext]['right_ips'] - peaks[ext]
323             ]),
324             fmt='x',
325             label='Prominences'
326         )
327
328     if self.can_plot:
329         for ax in axs: ax.legend()
330         plt.show()
331
332     # Transform data, skip if filename starts with 't'
333     if self.must_transform or not filename.name.startswith('t'):
334         wav2D, spec2D = self.transform(wav2D, spec2D, self.can_plot)
335
336     # Convert to 1D spectra
337     wav1D = np.median(wav2D, axis=1)
338     spec1D = np.median(spec2D, axis=1)
339
340     # Remove continuum
341     if self.cont_ord > 0:
342         for ext in range(2):
343             # spec1D_init[ext] = self.remove_cont(spec1D_init[ext],
344             #                                     ↪ wav1D[ext])
345             # spec1D[ext] = self.remove_cont(spec1D[ext],
346             #                                     ↪ wav1D[ext])
347             pass
348
349     if self.can_plot:
350         # Plot transformed & normalized feature widths
351         plt.plot(spec1D_init[0], label="O, initial")
352         plt.plot(spec1D_init[1], label="E, initial")
353         plt.plot(spec1D[0], label="O spec")
354         plt.plot(spec1D[1], label="E spec")
355         plt.legend()
356         plt.show()
357
358     # Find observed skylines
359     # skyline_cols, properties = find_peaks(sky_norm,
360     #                                         ↪ prominence=0.2) # 1000
361     # prominence is basically the ylimit above which peaks should
362     # be found
363     skyline_cols, skyline_wavs, properties = [], [], []
364     for ext in range(2):
365         cols, prop = signal.find_peaks(wav1D[ext], spec1D[ext],
366                                         ↪ prominence=1)
367         skyline_cols.append(cols)
368         properties.append(prop)
369         skyline_wavs.append(wav1D[ext, cols]) # col_to_wav(coeff2,
370         ↪ skyline_cols)
371
372     plt.plot(wav1D[ext, cols], cols, label='Observed')
373     plt.xlabel('Wavelength ($\AA$)')
374     plt.ylabel('Counts')
375     plt.legend()
376     plt.show()
377

```

```

372     for ext in range(2):
373         for i in range(len(skyline_cols[ext])):
374             logging.debug(("skylines - found features:\n"
375                         f"{properties[ext]['right_bases'][i] - "
376                         f"properties[ext]['left_bases'][i]:4d}\t"
377                         f"{skyline_cols[ext][i]:4d} - "
378                         f" {skyline_wavs[ext][i]:.1f} - "
379                         f" {properties[ext]['prominences'][i]:.2f}"
380                     ))
381
382
383     # Return results
384     return
385
386
387     # Plot results
388
389     # Find deviation of observed skyliners from known skyliners
390
391     # Load known skyliners
392     skyliners = self.load_sky_lines()
393
394     # Save results
395     raise NotImplementedError
396
397
398     def show_frame(self, frame: np.ndarray, title: str = None, label:
399     ↪ str = None, std: int = 1) -> None:
400         if not self.can_plot:
401             return
402
403         fig, axs = plt.subplots(2, 1)
404         axs[0].set_title(title)
405         axs[0].imshow(
406             frame[0],
407             label=f"O beam - {label}",
408             vmin=frame[0].mean() - std * frame[0].std(),
409             vmax=frame[0].mean() + std * frame[0].std()
410         )
411         axs[1].imshow(
412             frame[1],
413             label=f"E beam - {label}",
414             vmin=frame[1].mean() - std * frame[0].std(),
415             vmax=frame[1].mean() + std * frame[0].std()
416         )
417         for ax in axs: ax.legend()
418         plt.show()
419
420
421
422     # MARK: Process all listed images
423     def process(self,) -> None:
424         if self.beams == 'OE':

```

```
425     for fl in self.fits_list:
426         logging.info(f'{fl} skylines of {fl}.')
427         self.skylines(fl)
428         self.plot()
429
430     if self.beams in ['O', 'E']:
431         for fl in self.fits_list:
432             logging.info(f'{self.beams} skylines of {fl}.')
433             self.skylines(fl)
434             self.plot()
435
436     return
437
438
439 # MARK: Main function
440 def main(argv) -> None:
441     return
442
443 if __name__ == "__main__":
444     main(sys.argv[1:])
```


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List of Acronyms

IRAF	Image Reduction and Analysis Facility
POLSLT	Polarimetric reductions for SALT
STOPS	Supplementary Tools for POLSLT Spectro-polarimetry
ADC	Analog-to-Digital Converter
BPM	Bad Pixel Map
CCD	Charged-Coupled Device
CLI	Command Line Interface
CMOS	Complementary Metal-Oxide-Semiconductor
FITS	Flexible Image Transport System
FWHM	Full Width at Half Maximum
GUI	Graphical User Interface
HDU	Header Data Unit
HET	Hobby-Eberly Telescope
HRS	High Resolution Spectrograph
L+45°	Linear +45° Polarized
L-45°	Linear -45° Polarized
LCP	Left Circularly Polarized
LHP	Linear Horizontally Polarized
LVP	Linear Vertically Polarized
NIR	Near Infra-Red
NIRWALS	Near Infra-Red Washburn Labs Spectrograph
RCP	Right Circularly Polarized
RSS	Robert Stobie Spectrograph
S/N	Signal-to-Noise Ratio
SAAO	South African Astronomical Observatory
SALT	Southern African Large Telescope
SALTICAM	SALT Imaging Camera
UV	Ultraviolet
VPH	Volume Phase Holographic