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# SALT Spectropolarimetric Pipeline Comparisons

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Blazars are active galactic nuclei (AGN) with jets aligned very closely to our line of sight. The optical emission of blazars is often dominated by the polarised, non-thermal emission arising in the jets, with an underlying unpolarised, thermal emission component arising from the host galaxy, dusty torus, and accretion disk components.

Coupled with multi-wavelength observations, optical spectropolarimetry of blazars during both flaring and quiescent states can be used to disentangle the polarised and unpolarised components in their spectral energy distributions, providing better constraints for the non-thermal particle distribution. To this end, spectropolarimetry of blazars during different states of activity was taken with the Southern African Large Telescope (SALT) using the Robert Stobie Spectrograph (RSS). For RSS spectropolarimetry, reductions are performed using the POLSALT pipeline. In order to streamline the spectropolarimetric reductions, we have implemented supplementary interactive tools which provides additional wavelength calibration to improve the accuracy of the wavelength calibration for the O & E beam.

Here we present a brief overview of the tools and the results for Hiltner 652, a spectropolarimetric standard, as well as results for the blazars 3C 279. The reduced, $P_Q$ and $P_U$, Stokes parameters of Hiltner 652 show no major deviation from previously published results which reassures us that there is no interference introduced into the Stokes parameter calculations when wavelength calibrations are handled by our supplementary tools. The $\sim 6000-9000$ Å range of 3C 279 shows a notable dip in the normalized spectrum during a period of flaring when compared to epochs of enhanced activity. The degree of polarisation for 3C 279 of 13.2%, 9.5%, and 21.2% for the epochs 2017 March 28, 2017 March 31, and 2017 May 17, respectively, remains fairly constant across the observed wavelength ranges while still varying with the blazars' state of quiescence or flaring.

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## 1. Introduction

Blazars are a radio-loud sub-set of Active Galactic Nuclei (AGN), where the jet is aligned very closely to our line of sight and whose observed emission varies over time scales from hours to decades [1]. The optical emission observed from blazars is often dominated by the polarised, non-thermal emission arising in the jets, but there is also underlying non-polarised, thermal emission arising from the host galaxy, dusty torus, and accretion disk components [2]. When a blazar varies between flaring and quiescent states, the relative strength of the thermal component to the non-thermal component changes.

The Spectral Energy Distribution (SED) of blazars shows two clear components: a lower energy component produced through leptonic synchrotron processes (covering the radio to the UV/soft X-ray regimes) and a higher energy component (covering the X-ray to the $\gamma$-ray regimes) which can be produced through either leptonic or hadronic processes [3]. Optical spectropolarimetry observations, coupled with multi-wavelength observations during both flaring and quiescent states, can be used to disentangle the polarised and non-polarised components in the blazar's SED, providing better constraints for the non-thermal particle distribution [4, 5].

To this end, spectropolarimetric observations of blazars during different states of activity were taken using SALT [6] and the RSS [7]. RSS spectropolarimetry data is reduced with the dedicated POLSALT pipeline [8]. In order to facilitate the blazar observations we have developed supplementary tools to provide a more interactive approach to the wavelength calibration, allowing for improved accuracy for the O & E beam wavelength solutions [9]. Furthermore, spectropolarimetric standards, which were also observed with SALT and the RSS, were reduced alongside the blazar observations to test that the developed tools correctly performed the wavelength calibration. Here we present an overview of the pipeline as well as the preliminary results of a spectropolarimetric standard, namely Hiltner 652, and for the blazar 3C 279.

## 2. Pipeline Overview

RSS spectropolarimetry data is currently reduced using the POLSALT pipeline [8]. This python package allows for a full reduction from pre-reduction to extracted spectrum, and measured polarisation. However, the wavelength calibration component of the package does not allow for flexibility, nor provide a tool to confirm that the wavelength calibrations of the O & E beams are in agreement. This flexibility is most notably missed when performing calibrations of observations taken using the PG0300 grating[1] due to the very sparse spectral features of the Argon arc lamp used by SALT as well as second order contamination which differs between the O & E beams.

The developed tools work in conjunction with the existing pipeline and provide a method to perform the wavelength calibrations using conventional IRAF [10] methods. Figure 1 shows the typical workflow for data reductions of spectropolarimetric SALT data. Items in blue refer to processing steps completed entirely using POLSALT while items in orange refer to processing steps completed using the developed tools. The single green item refers to the wavelength calibration

[1]This grating has been decommissioned and replaced by the PG0700, and is not available for general use as of November 2022.

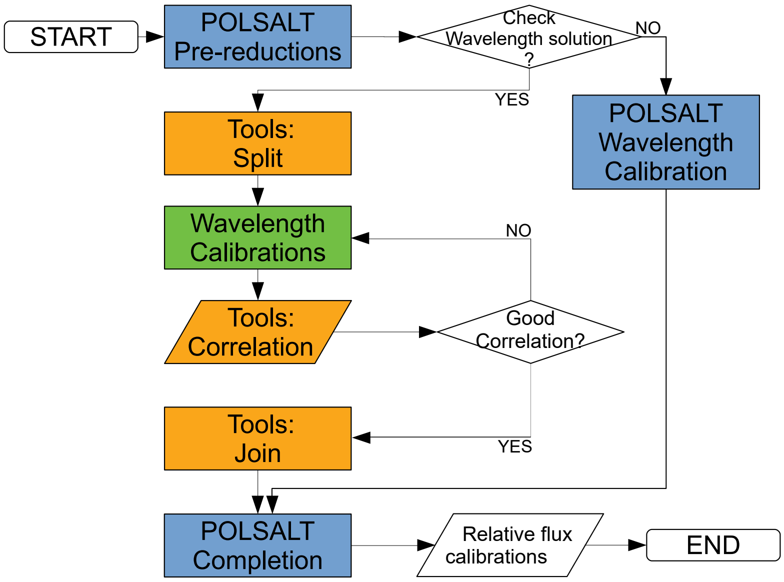


**Figure 1:** A general workflow for data reductions using a combination of POLSALT and our developed tools.

| Source | Observation date | Grating angle (°) | Slit width (") | Exposure time (sec) | Wavelength range (Å) |
|---|---|---|---|---|---|
| Hiltner 652 | 2022 June 10 | 12.878 | 2 | 48.5 | 3350 - 6440 |
| 3C 279 | 2017 March 28 | 12.5 | 1.5 | 480.8 | 3300 - 6300 |
| 3C 279 | 2017 March 28 | 19.625 | 1.5 | 480.8 | 5800 - 8800 |
| 3C 279 | 2017 March 31 | 12.5 | 1.5 | 480.8 | 3300 - 6300 |
| 3C 279 | 2017 March 31 | 19.625 | 1.5 | 480.8 | 5800 - 8800 |
| 3C 279 | 2017 May 17 | 12.5 | 1.5 | 720.8 | 3300 - 6300 |
| 3C 279 | 2017 May 17 | 19.625 | 1.5 | 720.8 | 5800 - 8800 |

**Table 1:** All spectropolarimetric observations taken with SALT and the RSS and used as part of development and testing of the supplementary tools.

done in IRAF. Additional tools to cross-check that the wavelength calibration is consistent across both beams have also been implemented.[2]

## 3. Observations

The spectropolarimetric observations were taken using the RSS mounted on SALT, in LINEAR mode. The spectropolarimetric standard, Hiltner 652, was observed in 2022 and the blazar 3C 279, was observed in 2017, as summarized in Table 1. All observations presented here were observed using the PG0900 and were reduced following the reduction workflow as described in Figure 1.

[2] A further, in-depth, discussion of the developed tools can be found at [9].

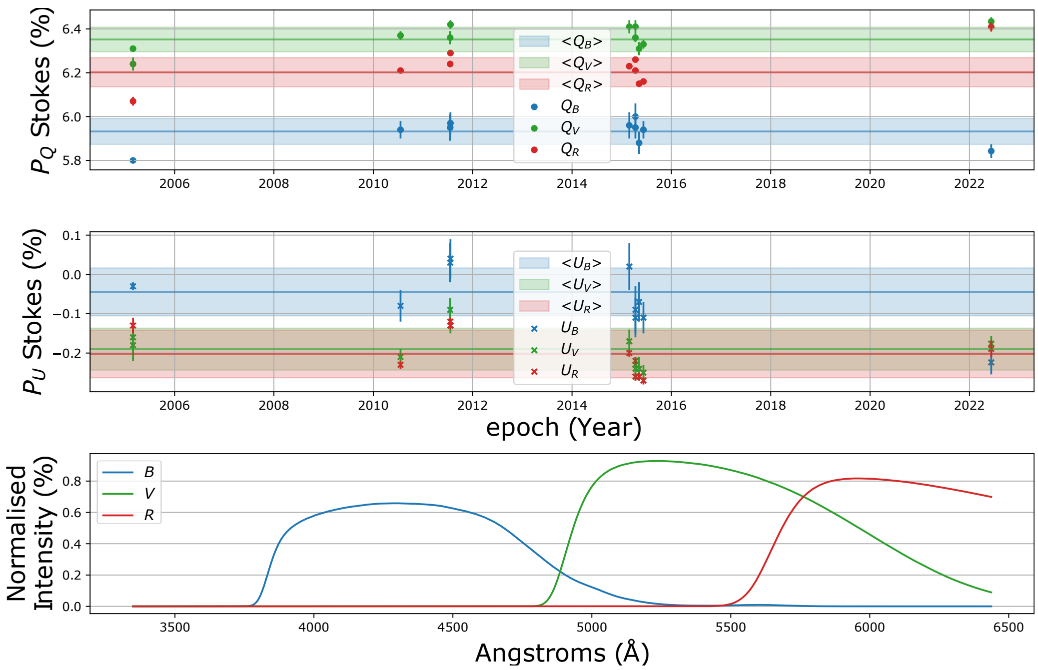


**Figure 2:** The reduced Q and U Stokes parameters for Hiltner 652 obtained with SALT in 2022 (post 2020) calculated by convolving the spectropolarimetry with the Johnson-Cousins filter pass-bands. This is compared to the published FORS1 [11] and FORS2 [12] observation results (top and middle panels). The average of the FORS reduced Stokes parameters as well as their standard deviation are plotted as the horizontal lines and shaded regions, respectively. Hiltner 652 was observed by SALT in 2022, by FORS1 from 1999 to 2006 (shown as average value at March 2005), and by FORS2 from 2010 to 2016. Finally, the Johnson-Cousins filter pass-band's used by POLSALT to calculate the stokes parameters in the different filters are shown in the bottom panel.

## 4. Results

The linear Stokes parameters, $Q$ & $U$, normalized to the total intensity, referred to henceforth as the reduced Stokes parameters, $P_Q$ & $P_U$, are relative quantities which are used to calculate the polarisation properties, and from which the fraction of linear polarisation may be easily calculated as $P_L = \sqrt{P_Q^2 + P_U^2}$ [13]. The reduced Stokes parameters of Hiltner 652, convolved against the Johnson-Cousins filter pass-bands, as performed by POLSALT, are shown in Figure 2 and are compared against published filtered reduced Stokes parameters obtained with FORS1 [11] and FORS2 [12]. The bottom panel of Figure 2 also shows the filter band-passes for the wavelength range covered by the SALT spectropolarimetry; note that the full $R$ band is not covered by the observation setup.

The reduced Stokes parameters of Hiltner 652 fall within or near the $1\sigma$ level of the previously published reduced Stokes parameters over the course of multiple years. This shows that Hiltner 652 is not only a good standard for spectropolarimetric observations but also that using POLSALT with the supplementary wavelength calibrations correctly calculated the Stokes parameters.

The blazar 3C 279 was observed during periods of enhanced and flaring $\gamma$-ray activity for energies of 0.1 – 100 GeV and were sourced from the Fermi Light Curve Repository (Fermi LCR)

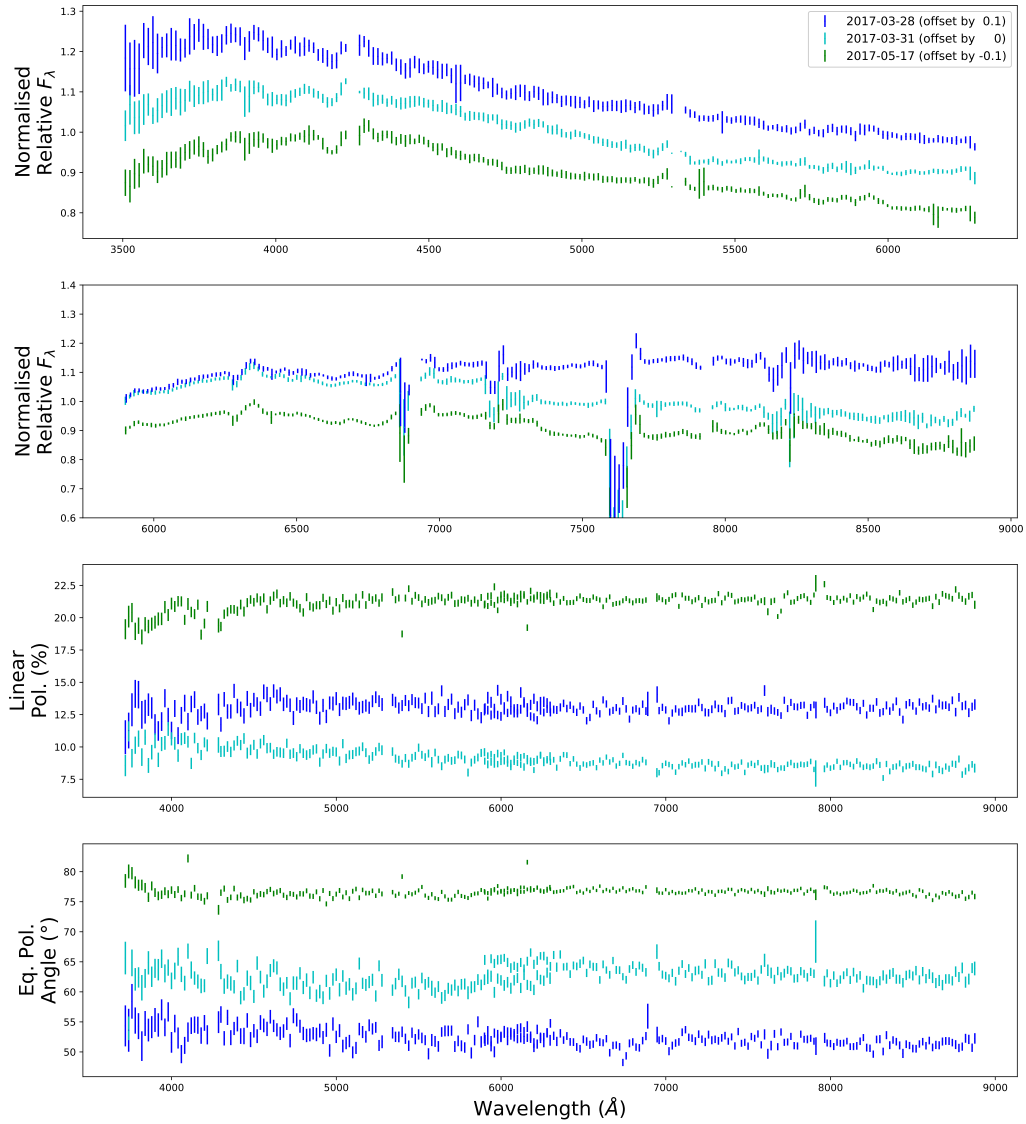


**Figure 3:** Optical spectropolarimetric observations of 3C 279 during two different periods of flaring. The relative flux calibrated spectra for the grating angles 12.5° (top), observed first at each epoch, and 19.625° (second from top), the degree of polarisation (third from top), and the polarisation angle (bottom).

[14]. 3C 279 was observed at fluxes of $1.58\times10^{-6}$, $2.87\times10^{-6}$, and $2.00\times10^{-6}$ph cm$^{-2}$ s$^{-1}$ as compared to a 'quiescent' median flux of $4.59\times10^{-7}$ph cm$^{-2}$ s$^{-1}$.

Figure 3 shows the relative flux calibrated spectra normalized to the spectrum's mean (and offset as indicated), degree of polarisation, and polarisation angle for 3C 279. The relative flux was normalized to better compare how the shape of the spectrum changes during the differing $\gamma$-ray states. 3C 279 showed variable flux and polarisation during the three observations, with the polarisation changing by $\sim$ 12.23 % and the angle changing by $\sim$ 24.22°. The relative spectral shape remains similar over all three observations, however the second observation (2017-03-31) appears to show a slightly brighter spectrum in the blue. There is also a relatively good agreement in the polarisation at the wavelength overlap for the different grating angles. The difference of the polarisation and degree of polarisation is on the order of 0.25 % and 1.25°, respectively.

## 5. Discussion and Conclusions

In this paper we have considered the observations of a spectropolarimetric standard, Hiltner 652, and a flaring blazar, 3C 279, to test our supplementary tools used for the reduction of spectropolarimetric data obtained with the RSS. The results serve to confirm that the supplementary tools' wavelength reductions, in combination with POLSALT, produces the correct polarisation behavior. Our results for Hiltner 652 agree well with the historical results obtained using the FOcal Reducer and low dispersion Spectrograph (FORS1 and FORS2) mounted at the Very Large Telescope (VLT).

For 3C 279, there is similarly good agreement between the polarisation for the observations taken at two grating angles where the wavelength ranges overlap. Some disagreement is found which may be due to the inherent nature of flaring blazars which cause the polarisation angle to drastically vary and the two observations at different grating angles are not taken simultaneously. Additionally, the disagreement may be due to a lower Signal-to-Noise Ratio (SNR) at the edges of the RSS, which would introduce a larger systematic error. The lower SNR could originate from either blaze effects, or from the extraction of the trace, which is currently limited to a rectangular aperture in the current POLSALT pipeline.

The results show that our supplementary wavelength calibrations for POLSALT increase the efficiency of the data reduction and produce acceptable results. This reduction procedure has been used for the reduction of a number of blazar observations undertaken as part of a long term monitoring campaign [15].

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