Southern African Large Telescope

Polarimetry Observer's Guide

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Table of Contents

1 Scope 1

2 General considerations 1
  2.1 Data Collection 1
  2.2 Observing Parameters 1
  2.4 Polarimetric Calibrations 3

3 Grating Spectropolarimetry 3
  3.1 Longslit On-Axis 4
  3.2 Multiple Targets along Slit 5
  3.3 MOS Grating Spectropolarimetry 5

4 Imaging Spectropolarimetry 5
  4.1 Slitless Imaging Spectropolarimetry 6
  4.2 MOS Imaging Spectropolarimetry 6

5 Filter Imaging Polarimetry - Not Advised 7

1 Scope

This document provides advice for observers who wish to use SALT RSS spectropolarimetric modes. It includes a description and capabilities of the various modes, how to construct a proposal, use the PIPT to define polarimetric observations, calibrate and analyze data using the polsalt pipeline. Additional detailed description on the polsalt pipeline can be found in the Github Wiki: *https://github.com/saltastro/polsalt*

2 General considerations

2.1 Data Collection

The RSS polarimetric modes make use of a polarizing beamsplitter which may be inserted in the collimated beam just before the camera, which divides the 4′x 8′ polarimetric field of view into two subimages, "O" and "E", plus rotatable half- and quarter-wave plates which may be inserted after the SALT focal plane. Acquisition of stokes information requires a pair of successive images 1,2 with different waveplate rotation positions which effectively rotate linear polarization by 90° or reverse the circular polarization between them. The "raw stokes" signal is then

$$S = \tfrac{1}{2} \left[(O_1 - O_2)/(O_1 + O_2) - (E_1 - E_2)/(E_1 + E_2)\right]$$

This "doubly differential" technique removes to first order throughput variations between the two images and flatfield response differences between the two beams. Background is extracted from areas in the same images to obtain simultaneous background removal. Different sets of Q, U, and/or V stokes parameters are obtained by selecting a "Polarimetry Pattern" (Table 1 below) which cycles through a set of waveplate angles to collect the appropriate raw stokes data, which is then combined in the reduction into calibrated "final stokes" data.

Typical polarimetric observing condition requirements are non-photometric or thin cloud. Lunar background is not a problem for brighter objects (V> 12). What must be avoided is rapid changes in conditions (like patchy cloud) that cause major differences between the two images in a raw stokes pair. If one image out of the two is spoiled, both are then unusable.

For detector setup (see Table 1 below), "Fast" readout speed is fine, since polarimetry almost always requires collection of many photons, and hence exposures where sky background noise with a 10m telescope is far above detector noise. "Bright" gain works fine for bright objects where CCD saturation may be a problem.

2.2 Observing Parameters

Table 1 summarizes the polarimetric observing parameters that one must set in the RSS simulator and PIPT. The "Comment" column lists the choices recommended here. The reason for the recommendations is described elsewhere in this document.

PIPT/ RSS Sim Item	Selection	Configuration	Comment
Mode	Spectropolarimetry	Grating dispersion	all gratings
	Imaging Polarimetry	Beam-splitter dispersion	in commissioning
Polarimetry Pattern	Linear	I,Q,U: two HW pairs	usual choice
	Linear-Hi	I,Q,U: four HW pairs	for commissioning
	Circular	I,V: one QW pair	in commissioning
	Circular-Hi	I,V: four QW/ HW pairs	in commissioning
	All Stokes	I,Q,U,V: 3 QW/ HW pairs	in commissioning
	User-defined		used for calibrations
Cycles	Repeats of Pattern		do at least 3
Beamsplitter Orientation	normal	split in rows	use this
Slit Type	Polarimetric Longslit	slit: 4' x 0.6",1.25",1.5",4"	all supported
	MOS	grating or imaging	not yet supported
Grating settings	Same as non-pol		> 3600 Å only
Arc	Grating modes only		
Detector mode	Normal	full readout with shutter	use this
Iterations	exposure repeats		1; do not use >1
Prebinned Rows	2 or 4		2 in slit width direction
Prebinned Columns	2 or 4		2 in slit width direction
Gain	Faint,Bright		use Faint or Bright
Readout Speed	Fast,Slow		use Fast
Detector Window	arcsec window limit		do not select

Table 1. Observing Parameters

2.3 Precision

Assessing precision is a critical aspect of polarimetry, because it often relies on very small differences between two signals. Reliable error bars are necessary to convince a paper referee. The reduction pipeline assesses the readout noise and photon statistics of each bin in the raw data, and a variance (and covariance) plane is propagated through the analysis. Repeatability experiments have demonstrated that usually the precision is accurately reflected by those statistics. However, because data must be extracted to high signal/noise to achieve this, systematic errors can easily creep in. Thus, we advise that any polarimetric observation be repeated at least 3 times ("Cycles" in Table 1) to assess the precision. (You should not use "Detector Iterations" to do this: this has not proven to give reliable precision estimates for polarimetry). The analysis pipeline provides "chisq" and "systematic err" outputs by comparing the redundant data.

2.4 Polarimetric Calibrations

Also important for polarimetry is accuracy, which is provided by calibrations. The intent is to have relevant polarimetric calibrations maintained by SALT, and applied during standard pipeline reduction. Polarimetric calibration can depend on wavelength, target position in the Field Of View, and position of the SALT tracker. Some may depend on time. There are three types of calibrations for linear polarization: zero-point (sometimes called "instrumental polarization"), efficiency (mainly waveplate optical axis), and mechanical zero-point. Also, two types for circular polarization, zero-point and efficiency, and one for linear-to-circular conversion. Table 2 summarizes the status of these six. Calibration is complete for the on-axis linear polarization types, though the dependence of this on track position is still currently being determined. The variation with track position appears to be mainly in PA, with a "ripple" in wavelength over several hundred Angstroms which can be seen in stars with high interstellar polarization. The FOV dependence, which appears to be mainly a similar ripple, is also currently being determined.

		Status			Precision		
Calibration	Origin	On-Axis	Full FOV	Full Track	On-Axis	Full FOV	Full Track
Linear Pol Zero-Point	Mirrors, waveplate	Done	in work	in work	0.05%	1.5%	0.1%?
Linear Pol Efficiency	Waveplate	Done	in work	in work	0.2° ripple	0.5° ripple	0.5° ripple
Linear Pol PA Zero-Point	Rho, waveplate rotator	Done	NA	NA	0.1°		
Circular Pol Zero-Point	?, likely negligible	TBS	TBS	TBS			
Circular Pol Efficiency	Waveplate	TBS	TBS	TBS			
Linear-Circular Conversion	ADC, Waveplate	TBS	TBS	TBS			

Table 2. Calibrations

3 Grating Spectropolarimetry

The RSS gratings divide into two categories, one low resolution 300 ℓ/mm surface relief ("SR") and five moderate resolution Volume Phase Holographic ("VPH") gratings. The SR grating is blazed at about 5500 Å, usable 3700 - 10500 Å, and the whole spectrum fits on the detector at a single grating angle. Normally this would require a color filter to separate orders if data is required above 7400 Å, since the wavelength ranges over more than a factor of two, but in polarimetric mode, the beamsplitter provides enough cross-dispersion that the first and second order are separated. Therefore, with this grating, a color filter like the 3400 Å, which is the default in the PIPT (to suppress blue background) is adequate, and the entire wavelength range can be obtained in one setting. The pipeline standard is to extract the first order and avoid the second, which does not have useful signal. The VPH gratings are used just as in non-polarimetric mode, with the color separator suggested by the PIPT. Currently, we do not advise going below 3600 Å, even though the 900 and 3200 ℓ/mm gratings are sensitive there. This is because the arc lamps do not currently go there, and good relative wavelength calibration of the two beams is required to match E and O.

For wavelength calibration, one should select the arc lamp suggested by the PIPT (end of observation). A single image will be obtained with the beamsplitter in, resulting in separate E and O arcs, corresponding to the science images. The pipeline reduction will identify and calibrate both as a function of position along the slit. One should attempt to use similar identifications for the two beams, in order to get a good relative calibration.

The analysis does provide an intensity spectrum by summing the E and O beams. If one wishes to flux-calibrate this, one will need to provide (and request execution of) a "P4" block named Cal_SPST, using the same parameters as the science blocks, requesting two exposures of 120 sec using a "user-Defined" Pattern with one HW position only. Any target may be specified, with the comment:

"Twilight spectrophotometry calibration block, to be used for all science blocks. Any specphot standard is OK, but double the usual exposure to account for beamsplitter. Run the "User-defined" spectropolarimetry pattern, which has just one position of the waveplate, two detector exposures (for backup)."

The pipeline will generate a "fluxdb" file from this data, which can be copied to subsequent nights for use there. The color-dependence of the flux calibration at a particular polarimetric configuration does not change appreciably between nights.

3.1 Longslit On-Axis

The most frequently requested RSS polarimetry is longslit grating spectropolarimety of a single target placed on-axis in the FOV. This results in two orthogonally polarized spectra, "O and "E", placed on the bottom and top of the detector (Figure 1).

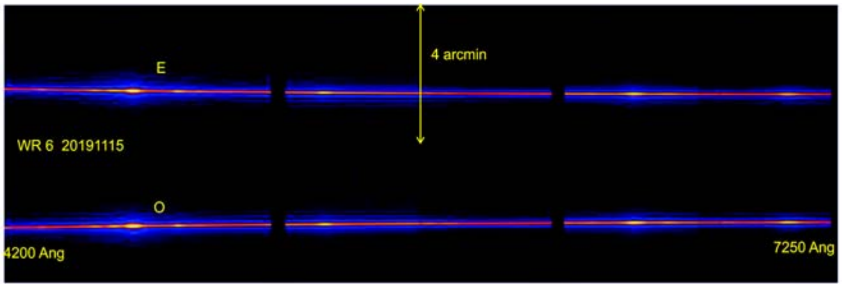

Figure 1. Single target longslit spectropolarimetry

Predicted performance may be obtained using the RSS simulator, specifying "Use Polarimetry" on the "Spectroscopy" tab. Choosing SNR per spatial and spectral resolution element, then "make an exposure", will show the photon-limited SNR/ spectral resolution element for the target summed over the slit, after removal of sky background The predicted error for the whole observation, including all cycles, per resolution element in the degree of polarization Q/I, U/I, or V/I for each stokes parameter will be

relative error = sqrt(# polarization stokes parameters)/SNR

(e.g., for linear polarimetry Q/I and U/I, and thus P/I, *√2/SNR*).

Analysis of the data, using standard extraction aperures for target and background, may be simply performed using a standard python script "reducepoldata_sc.py" available and described at the polsalt GitHub.

3.2 Multiple Targets along Slit

Sometimes one may wish to take advantage of the fact that RSS is an imaging spectrometer, and obtain multiple results along the slit simultaneously. If there are multiple targets separated by intervals of background, this may be done in longslit mode as usual, using a GUI at the polsalt GitHub to define the different targets (see below). (Note, however, that the off-axis polarimetric calibration has not been completed, see Table 1, so that publishable results will have to await completion of this effort.)

If, however, one wishes to obtain spatially resolved spectropolarimetry on a continuous diffuse object along the slit, it will be necessary to separate the diffuse targets by a custom multi-object longslit which is divided into "slitlets", see MOS below. If one just tries to do the separation with the extraction aperture at the detector, one has to do it separately in the E and O beams, the exact separation point will be inevitably different, and it will change with guiding and seeing. This introduces uncontrollable intensity differences into the polarimetry signal, which is always much smaller than the intensity. If, on the other hand, one does the separation using a slit edge, this is done at the focal plane before the beamsplitter, so any change due to seeing and guiding are the same in the E and O beams.

TBS: Using the specpolreducedata GUI

3.3 MOS Grating Spectropolarimetry

Grating spectropolarimetry of multiple objects over the full polarimetric FOV using a custom MOS slitmask is a mode that is possible, but is still in commissioning. The PIPT does not yet allow for this. Precision should be similar to on-axis results, so the RSS simulator can be used separately for each target, though the spectral coverage is shifted by horizontal placement in the FOV.

A future version of pySlitMask (available at the GitHub) will allow for design of a polarimetric MOS slitmask. This is complicated by the reduced FOV, and by the fact that the spectropolarimetric spectra are curved on the detector.

Note, again, that the off-axis polarimetric calibration has not been completed.

4 Imaging Spectropolarimetry

Ang	Ang/resel	R
3400	90	38
4000	167	24
5000	368	14
6000	580	10
7000	919	8
8000	1112	7
9000	1347	7

Table 3. Prism Dispersion

The other major spectropolarimetric mode is imaging spectropolarimetry. To our knowledge, this is unique to RSS. If the spectrograph is in imaging mode (straight through, no filter, no grating), with the beamsplitter in place, each point object in the field of view is dispersed (in opposite directions) into an O and E mini-spectrum along the splitting axis by the chromatic splitting variation in the beamsplitter. The full RSS spectral range in these mini-spectra covers about 20 arcsec. Spectral resolution increases sharply into the blue (Table 3, which assumes 1.5 arcsec spatial resolution), typical for prism dispersion. This mode may be done either slitless (using a 4x8 arcmin imaging mask), or MOS, with slitlets oriented perpendicular to the grating-mode slits. Both submodes are in commissioning. Figure 2 shows a sample image for slitless imaging spectropolarimetry. This is a typical use for imaging spectropolarimetry, obtaining very low spectral resolution spectropolarimetry of all stars in the field of a program star, here the Wolf-Rayet star WR 97, to estimate the interstellar polarization to be removed from WR 97 grating spectropolarimetry.

Wavelength calibration in imaging spectropolarimetry mode is obtained not with an arc lamp, but rather by taking single images in the imaging spectropolarimetry configuratioin, introducing different (two is typical) interference filters so that two points in the dispersion of each star are determined. These images also serve to allow automatic catalog identification of the target stars. Unlike grating mode, these calibration images should be done before the spectroopolarimetry, since they require availability of the target, which is often lost at the end of an observation.

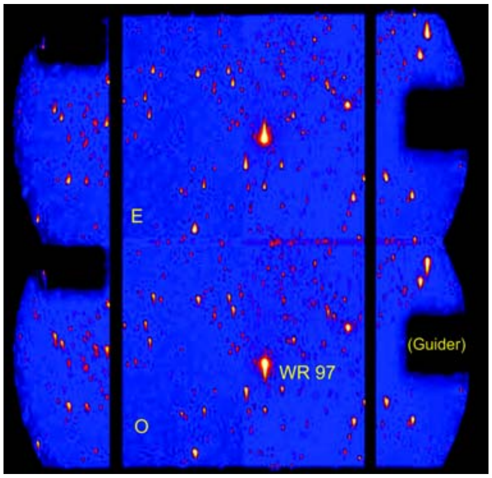

Figure 2. Slitless Imaging Spectropolarimetry

Because of the very low spectral reolution, large bandwidth, and lack of grating and filter, exposures are typically very short to avoid saturation, (V=11 saturates in 5 seconds with the detector in BRIGHT/FAST), and observations of faint targets (V=18 is easy) are enabled. Observations may use many cycles (8 is typical), but still last only a few hundred seconds

4.1 Slitless Imaging Spectropolarimetry

This mode is typically useful for quick pilot assessments, since the observation is short, and easy to specify and carry out. However, practical limitations of the slitless mode mean that extraction errors will likely prevent achievement of the SNR predicted by photon-statistics. These limitations include crowding, and guiding and seeing variations. Also, the sky at all wavelengths contributes to the background in the dispersed spectra, so is larger than one would get in slit mode by at least the R of the dispersion, like 10x. So bright moon is not advised.

In the PIPT, specify Imaging Polarimetry, BRIGHT/FAST, and 4x4 binning. In crowded fields and/or if UV is not of interest, it is advantageous to use a color filter (typically PC03850) to cut out the long faint UV tail of the dispersion of each star. Definitely use many cycles, to enable evaluation of the actual precision, since it is unlikely to be photon-limited.

The current pipeline (in development) requires a catalog with good astrometry to enable target identification. A python routine which accesses the Gaia archive is available to make such a catalog. The wavecal images are first reduced, to identify targets and establish wavelengths. Then the polarimetry cycles are processed, including a correction for image motion. Targets with bad crowding and images with poor seeing are culled.

4.2 MOS Imaging Spectropolarimetry

The advantages of going to MOS are that the slitless disadvantages are eliminated, so that photon-limited SNR is more likely. Also, sky background is much reduced. The disadvantage is that a slitmask must be designed and manufactured, and the MOS acquisition introduces risk and is time-consuming. However, it provides the best chance of going very faint.

Like MOS grating spectropolarimetry above, this submode is not yet supported.

5 Filter Imaging Polarimetry - Not Advised

While it is technically possible to do imaging polarimetry with a filter, it is not advised. With a diffuse target, no filter or a broad-band filter, the chromatic dependence of the beam-splitter destroys the imaging. The best choice in this case is to sample the diffuse target at many places using MOS imaging spectropolarimetry, above. With a collection of stellar targets and an interference filter, the throughput is cut drastically, and it makes more sense to use imaging spectropolarimetry, above, either slitless or MOS.