CIRCE+GTC Polarimetry Commissioning Report

1 CIRCE Polarimetry

The polarimetry mode of CIRCE provides measurement of the linear Stokes parameters in a single image, unlike standard dual-beam polarimeters. This is achieved with a wedged double wollaston (WeDoWo) (Charcos-Llorens, 2008)[1] implementation, in which the fast axis of one of the wollaston prisms is rotated 22.5 degrees and the same prism is tilted enough to separate two orthogonal pairs of sub-images. This design is the main strength of CIRCE polarimetry mode since fast polarimetric variability of interesting astrophysical sources can be investigated with simultaneous measurement of the q and u parameters. In addition, only two half wave plate (HWP) rotations can be used instead of all four to significantly reduce calibration/observing time.

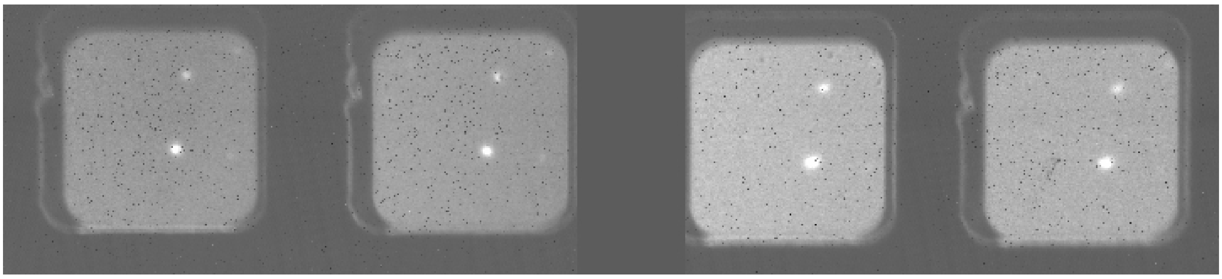

Figure 1: An example of a polarimetry data acquisition image with CIRCE, HWP at 0°.

Sub-images of four directional polarizations are aligned in the horizontal direction and each have a size about ∼110x110 pixels (or ∼11"x11"). Therefore, fast band readouts as narrow as 130 pixels can be used without losing any information in the field of view. The minimum integration time of these fast readouts is about 100 miliseconds. These readouts can be exploited for the purposes of fast data acquisition or observations of very bright targets without non-linearity/saturation. The lack of dim polarized/null standards is known to be a problem for imaging polarimetry with large telescopes, but CIRCE can offer observations of point sources as bright as 7th magnitude in K_s and H filters, or about 5th magnitude in J filter, even under excellent seeing conditions (about 0.5 arcsecond). Observations of brighter targets than these limits are still an option but should be discussed with UF CIRCE team.

There are four default rotation for the half-wave plate (HWP) of CIRCE. One of the orthogonal pairs, either (0°, 45°) or (22.5°, 67.5°), is sufficient to fully define the polarization state of a point source. The polarization directions of the four sub-images with respect HWP rotations are given in Table 1. We currently offer (0°, 45°) pair as the default.

HWP	o1	e1	o2	e2
0°	↑	→	↗	↘
45°	→	↑	↘	↗
22.5°	↗	↘	↑	→
67.5°	↘	↗	→	↑

Table 1: Polarization information of sub-images with respect to HWP angle.

[1] http://adsabs.harvard.edu/abs/2008SPIE.7014E..2MC

With this configuration, q and u measurements can be obtained with the following equations,

$$q(0°/45°) = \frac{\sqrt{o1(0°)e1(45°)} - \sqrt{o1(45°)e1(0°)}}{\sqrt{o1(0°)e1(45°)} + \sqrt{o1(45°)e1(0°)}} \quad (1)$$

$$u(0°/45°) = \frac{\sqrt{o2(0°)e2(45°)} - \sqrt{o2(45°)e2(0°)}}{\sqrt{o2(0°)e2(45°)} + \sqrt{o2(45°)e2(0°)}} \quad (2)$$

$$q(22.5°/67.5°) = \frac{\sqrt{o1(22.5°)e1(67.5°)} - \sqrt{o1(67.5°)e1(22.5°)}}{\sqrt{o1(22.5°)e1(67.5°)} + \sqrt{o1(67.5°)e1(22.5°)}} \quad (3)$$

$$u(22.5°/67.5°) = \frac{\sqrt{o2(22.5°)e2(67.5°)} - \sqrt{o2(67.5°)e2(22.5°)}}{\sqrt{o2(22.5°)e2(67.5°)} + \sqrt{o2(67.5°)e2(22.5°)}} \quad (4)$$

2 Observing Procedure and Calibrations

2.1 Standard Observing Procedure

Once per night before observing, we suggest a datum of the linear slide and HWP mechanisms. CIRCE should be focused before slewing to a target for polarimetry observations. The standard polarimetry observing procedure of a target is given below:

1. Slew to the target and acquire a single frame image.
2. Move the target to the desired polarimetry location in the frame.
   (or click "Polarimetry Offset" button)
3. Move the grism wheel to `WOLLY` and the linear slide to `FULL_F_IMAGING` position.
4. Acquire a single frame image. Target should be well-centered in four sub-images.
   If not, do a manual offset and take another image to confirm. Repeat if necessary.
5. Switch to band mode and set necessary detector parameters.
   (This should be included in the XML file. What it needs to do: switch from full frame to band mode, set to a default start and end row that we determine)
6. Start the observing sequence.
7. While the sequence is active, keep checking images for each dither(!!).
8. Switch to full frame and set necessary detector parameters.
9. Move the grism wheel to `OPEN` and linear slide to `RETRACTED` position.

2.2 Observing Sequences

The single dither position observing time should be at least 20 seconds for effective use of telescope time (for $> 50\%$ duty cycle) and not more than 35-40 seconds due to the variable infrared sky (up to 60 seconds for J filter). The only option for bright targets (< 9 mag for K_s and H, < 8 mag for J) is a configuration of 100 ramps each with 100 ms exposure time. Fainter targets can be observed with the configuration of 30 ramps each with 1 s exposure time. If faint targets are of interest (> 12 mag for all filters), the observing configuration can be set to 6 ramps each with 5 s exposure time (or 6 ramps each with 10 s exposure time for J filter). These configurations provide a total exposure time about 5 minutes when a five-point dither is used. We suggest a five-point or a three-point dither on a line as the default dithering configurations. Customized dithering sequences can be applied for special requirements but should be discussed with the UF CIRCE team.

2.3 Calibration: During Observing

For the best final data quality, a polarized standard should be observed before and after the science observations with all filters of interest. In addition, a null standard should be observed at least once per night. The actual observing time for the standard stars (bright ones) is less than 6 minutes per filter for five-point dither. The principal investigator (PI) should be aware of additional time for the preparation of polarimetry mode when switching targets. It is more effective to obtain multiwavelength polarization observations because no additional preparation is necessary when switching filters. We will point observers to lists of possible calibration standards, and polarimetric measurements of standard stars observed with CIRCE as the list develops. (In progress)

2.4 Calibration: Day Time

Polarimetric observations require ideally **9 repeats** of dark readouts for each detector configuration used during observations. Since the twilight sky is known to be intrinsically polarized, dome flats should be obtained at all filters and HWP rotations (should be 0 and 45) with the observations taken. During the procedure, the telescope should point to the **Zenith** and **Group 1** lamps should be used, at a level of **5% for K_s and H, at 25% for J.** Typical readout configuration should be **30 ramps each with 100 ms exposure time** while band readout centering the bright sub-images in the vertical direction.

We give the following sequence as an example for flatfield obtaining procedure;

- K_s filter, HWP at 0, lamps at 5%
- K_s filter, HWP at 45, lamps at 5%
- K_s filter, HWP at 45, lamps off
- K_s filter, HWP at 0, lamps off
- H filter, HWP at 0, lamps off
- H filter, HWP at 45, lamps off
- H filter, HWP at 45, lamps at 5%
- H filter, HWP at 0, lamps at 5%
- J filter, HWP at 0, lamps at 25%
- J filter, HWP at 0, lamps at 25%
- J filter, HWP at 0, lamps off
- J filter, HWP at 0, lamps off

  Note: Each filter should be finished as soon as possible when it has started.

2.5 Data Reduction

There is no default software for the polarimetry mode of CIRCE. Standard NIR imaging data reduction steps can be followed as a default. Some useful information for data reduction (header refers to 0th HDU in the multi extension fits images unless noted otherwise):

- Band mode limits are specified in the header. `W_Y_BEG` is the first row starting from the bottom of the detector up to `W_Y_END`
- `ROT1` and `ROT2` are respectively the rotation angle from the beginning of the file to the end of the file. Reported values should be inserted into calibration equations.
- For full frame imaging data with CIRCE, first ramp images should be treated differently than the other ramps in terms of dark subtraction. For band readouts, it takes more than one ramp to get similar dark frames and it depends on how fast images were taken. To be safe, each ramp should be treated separately. Bad pixels can be detected from median combined darks.
- If desired, pick-up noise can be significantly reduced by a simple process. The CIRCE infrared array is read by 32 different channels, each refer to 64 pixels wide columns in the detector. Odd and even channels can be median combined to obtain master odd/even channel noise pattern. Then, these patterns can be subtracted from the images. For many purposes, this process provides decent reduction of pick-up noise.

3 Intrinsic Polarization: CIRCE+GTC

We observed three null standards over two periods of polarimetry commissioning at different instrumental position angles (IPA) with rotator tracking disabled. By definition, we assume that a null standard has (or is close to) the intrinsic polarization state of [I/I, Q/I, U/I] = [1, 0, 0]. In an ideal case, rthe esults of null standard observations should follow the following equations as IPA changes:

$$q = q_c + q_T \cos(2\pi(\theta/180°)) - u_T \sin(2\pi(\theta/180°)) = q_c + |P_T| \sin(2\pi(\theta/180°) + \phi_1) \quad (5)$$

$$u = u_c - u_T \cos(2\pi(\theta/180°)) - q_T \sin(2\pi(\theta/180°)) = u_c + |P_T| \sin(2\pi(\theta/180°) + \phi_2) \quad (6)$$

$$\phi_1 - \phi_2 = \pi/2 \quad (7)$$

where q_c and u_c are the instrumental polarization of CIRCE, q_T and u_T are the instrumental polarization of GTC. ($|P_T| = \sqrt{q_T^2 + u_T^2}$)

We use the following definitions throughout this report:

- q1: q(0°/45°) - polarization measurement from directional pairs (0°, 90°) when HWP at 0° and 45° degrees
- u1: u(0°/45°) - polarization measurement from directional pairs (45°, 135°) when HWP at 0° and 45° degrees
- q2: q(22.5°/67.5°) - polarization measurement from directional pairs (0°, 90°) when HWP at 22.5° and 67.5° degrees

- u2: u(22.5°/67.5°) - polarization measurement from directional pairs (45°, 135°) when HWP at 22.5° and 67.5° degrees

Standard dual-beam polarimeters are designed to obtain two of the parameters defined above ((q1, u2) or (q2, u1)). CIRCE allows measurement of pairs, (q1, u1) or (q2, u2), in a single frame, however, (q1, u2) and (q2, u1) pairs come from two different pupils in the optical system of the instrument. Therefore, the polarization over the optical beam obtained from the telescope is not fully averaged, and the polarization gradient of the components in the optical path, eg. primary mirror of the telescope, may affect our results. As a consequence, we apply the calibration equations (Eqn. 1-3) on the pairs (q1, u2) and (q2, u1) separately.

For the data calibration, we suggest the utilization of constant amplitude fits and systematics are limited to 0.19%, 0.17% and 0.29% respectively for K_s, H and J filters.

We observed the following null standards during polarimetry commissioning:

1. GJ 3753 - 12 50 04.279 +55 06 02.93
   J=11.6 H=11.1 K_s=11.1

2. BD+28 4211 - 21 51 11.021 +28 51 50.36
   Jmag=11.3 Hmag=11.4 Kmag=11.6

3. HD 331891 - 120 12 02.151 +32 47 43.71
   J=8.8 mag, H=8.8 mag, K_s=8.7 mag

For each filter, we report measurement of parameters (q1, u1, q2, u2), resulting calibration equations from model fits with rms values, plots of the models and residuals. In addition to the error values given in the tables, a systematic error of 0.1% is included for each data point to account for different sources and atmospheric conditions. We also perform the fits with variable and constant amptitude (black and red lines in the plots) since there is significant amplitude change towards J band for measurements of q2. However, we note that constant amplitude model yield reasonable RMS values within the requirements for CIRCE polarimetry.

Results of null standard observations with K_s filter are given below:

IPA(^{o})	q1	q2	u1	u2
-133	-1.96(0.09)	-0.47(0.11)	-0.14(0.09)	-0.03(0.10)
-43	-0.36(0.07)	0.47(0.09)	-0.02(0.08)	-0.83(0.09)
-89	-1.56(0.12)	-0.31(0.09)	-0.69(0.13)	-1.37(0.11)
136	-0.25(0.09)	0.75(0.09)	-0.24(0.10)	-1.14(0.12)
2	-0.73(0.11)	-0.01(0.11)	0.71(0.11)	0.70(0.14)
46	-1.86(0.09)	-0.67(0.10)	0.28(0.09)	0.17(0.07)
2	-0.53(0.02)	0.45(0.03)	0.72(0.02)	0.73(0.03)
92	-1.80(0.03)	-0.96(0.03)	-0.49(0.03)	-0.75(0.03)
-89	-1.61(0.04)	-	-0.79(0.04)	-
-133*	-1.92(0.03)	-	0.25(0.03)	-
13*	-1.22(0.03)	-	0.56(0.03)	-
11*	-1.14(0.02)	-	0.56(0.02)	-

Fit results with constant amplitude (RMS=0.19),

$$
\begin{aligned}
q1 &= -1.17(0.03) + 0.95(0.04)\sin(2\pi(IPA/180) + 0.81(0.01)\pi) \\
u2 &= -0.26(0.05) + 0.95(0.04)\sin(2\pi(IPA/180) + 0.81(0.01)\pi - \pi/2) \\
u1 &= -0.02(0.05) + 0.68(0.05)\sin(2\pi(IPA/180) + 0.84(0.03)\pi - \pi/2) \\
q2 &= -0.11(0.06) + 0.68(0.05)\sin(2\pi(IPA/180) + 0.84(0.03)\pi)
\end{aligned}
$$

and with variable amplitude (RMS=0.19),

$$
\begin{aligned}
q1 &= -1.17(0.03) + 0.94(0.06)\sin(2\pi(IPA/180) + 0.81(0.01)\pi) \\
u2 &= -0.26(0.05) + 0.97(0.06)\sin(2\pi(IPA/180) + 0.81(0.01)\pi - \pi/2) \\
u1 &= -0.02(0.05) + 0.64(0.06)\sin(2\pi(IPA/180) + 0.83(0.02)\pi - \pi/2) \\
q2 &= -0.11(0.06) + 0.75(0.08)\sin(2\pi(IPA/180) + 0.83(0.02)\pi)
\end{aligned}
$$

Results of null standard observations with H filter are given below:

IPA(^{o})	q1	q2	u1	u2
-133	-1.79(0.10)	-0.32(0.16)	-0.03(0.11)	0.26(0.08)
-43	-0.39(0.10)	0.33(0.08)	0.12(0.10)	-0.52(0.08)
-89	-1.41(0.09)	-0.36(0.07)	-0.71(0.09)	-0.64(0.06)
136	-0.31(0.06)	0.42(0.09)	-0.19(0.07)	-0.58(0.08)
2	-0.33(0.08)	0.16(0.08)	0.61(0.08)	0.67(0.08)
46	-1.84(0.09)	-0.35(0.08)	-0.11(0.09)	0.66(0.08)
2	-0.65(0.03)	-0.07(0.03)	0.60(0.03)	0.45(0.04)
92	-1.56(0.03)	-0.27(0.03)	-0.77(0.03)	-1.12(0.02)
-89	-1.61(0.05)	-	-0.83(0.05)	-
-109*	-1.64(0.03)	-	-0.75(0.03)	-
13*	-1.14(0.03)	-	0.53(0.03)	-
11*	-0.64(0.03)	-	0.53(0.02)	-

Fit results with constant amplitude (RMS=0.17),

$$q1 = -1.03(0.03) + 0.86(0.04)\sin(2\pi(IPA/180) + 0.79(0.01)\pi)$$
$$u2 = -0.13(0.04) + 0.86(0.04)\sin(2\pi(IPA/180) + 0.79(0.01)\pi - \pi/2)$$
$$u1 = -0.10(0.05) + 0.61(0.05)\sin(2\pi(IPA/180) + 0.94(0.03)\pi - \pi/2)$$
$$q2 = -0.08(0.06) + 0.61(0.05)\sin(2\pi(IPA/180) + 0.94(0.03)\pi)$$

and with variable amplitude (RMS=0.14),

$$q1 = -1.03(0.03) + 0.84(0.05)\sin(2\pi(IPA/180) + 0.79(0.01)\pi)$$
$$u2 = -0.12(0.04) + 0.89(0.06)\sin(2\pi(IPA/180) + 0.79(0.01)\pi - \pi/2)$$
$$u1 = -0.10(0.05) + 0.70(0.06)\sin(2\pi(IPA/180) + 0.96(0.03)\pi - \pi/2)$$
$$q2 = -0.07(0.06) + 0.38(0.09)\sin(2\pi(IPA/180) + 0.96(0.03)\pi)$$

Results of null standard observations with J filter are given below:

IPA(^{o})	q1	q2	u1	u2
-133	-1.25(0.26)	0.46(0.17)	-0.03(0.25)	0.21(0.27)
-43	-0.41(0.11)	0.23(0.12)	-0.19(0.11)	-0.61(0.13)
-89	-1.23(0.14)	0.03(0.13)	-1.33(0.14)	-0.96(0.13)
136	-0.01(0.11)	0.16(0.12)	-0.31(0.12)	-0.61(0.10)
46	-1.75(0.14)	-0.23(0.13)	-0.28(0.13)	0.10(0.13)
2	-0.42(0.08)	-0.04(0.03)	0.61(0.07)	1.01(0.05)
92	-1.67(0.04)	-0.07(0.04)	-1.08(0.04)	-0.83(0.04)
-67*	-1.15(0.04)	-	-0.78(0.04)	-
15*	-0.97(0.04)	-	0.39(0.03)	-
13*	-0.84(0.03)	-	0.35(0.03)	-

Fit results with constant amplitude (RMS=0.29),

$$q1 = -1.04(0.04) + 0.97(0.06)\sin(2\pi(IPA/180) + 0.79(0.01)\pi)$$
$$u2 = -0.05(0.06) + 0.97(0.06)\sin(2\pi(IPA/180) + 0.79(0.01)\pi - \pi/2)$$
$$u1 = -0.27(0.05) + 0.56(0.06)\sin(2\pi(IPA/180) + 0.95(0.04)\pi - \pi/2)$$
$$q2 = 0.02(0.07) + 0.56(0.06)\sin(2\pi(IPA/180) + 0.95(0.04)\pi)$$

and with variable amplitude (RMS=0.22),

$$q1 = -1.04(0.04) + 0.90(0.08)\sin(2\pi(IPA/180) + 0.79(0.01)\pi)$$
$$u2 = -0.04(0.06) + 1.02(0.08)\sin(2\pi(IPA/180) + 0.79(0.01)\pi - \pi/2)$$
$$u1 = -0.28(0.05) + 0.81(0.07)\sin(2\pi(IPA/180) + 0.99(0.03)\pi - \pi/2)$$
$$q2 = 0.04(0.07) + 0.07(0.10)\sin(2\pi(IPA/180) + 0.99(0.03)\pi)$$

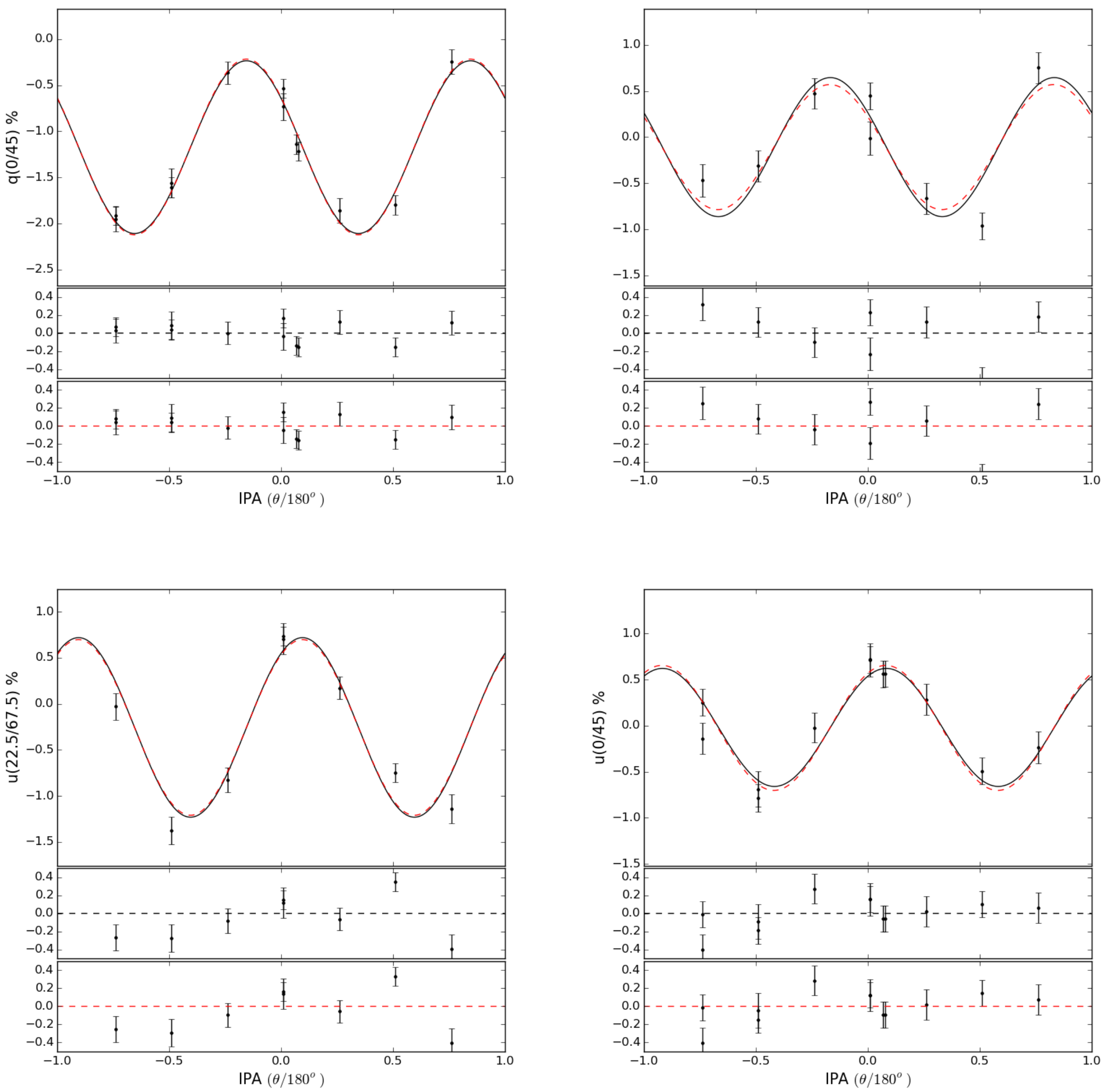

Figure 2: Instrumental polarization measurements with respect to IPA for K_s filter. Black line represent the variable amplitude fit and red line the constant amplitude fit

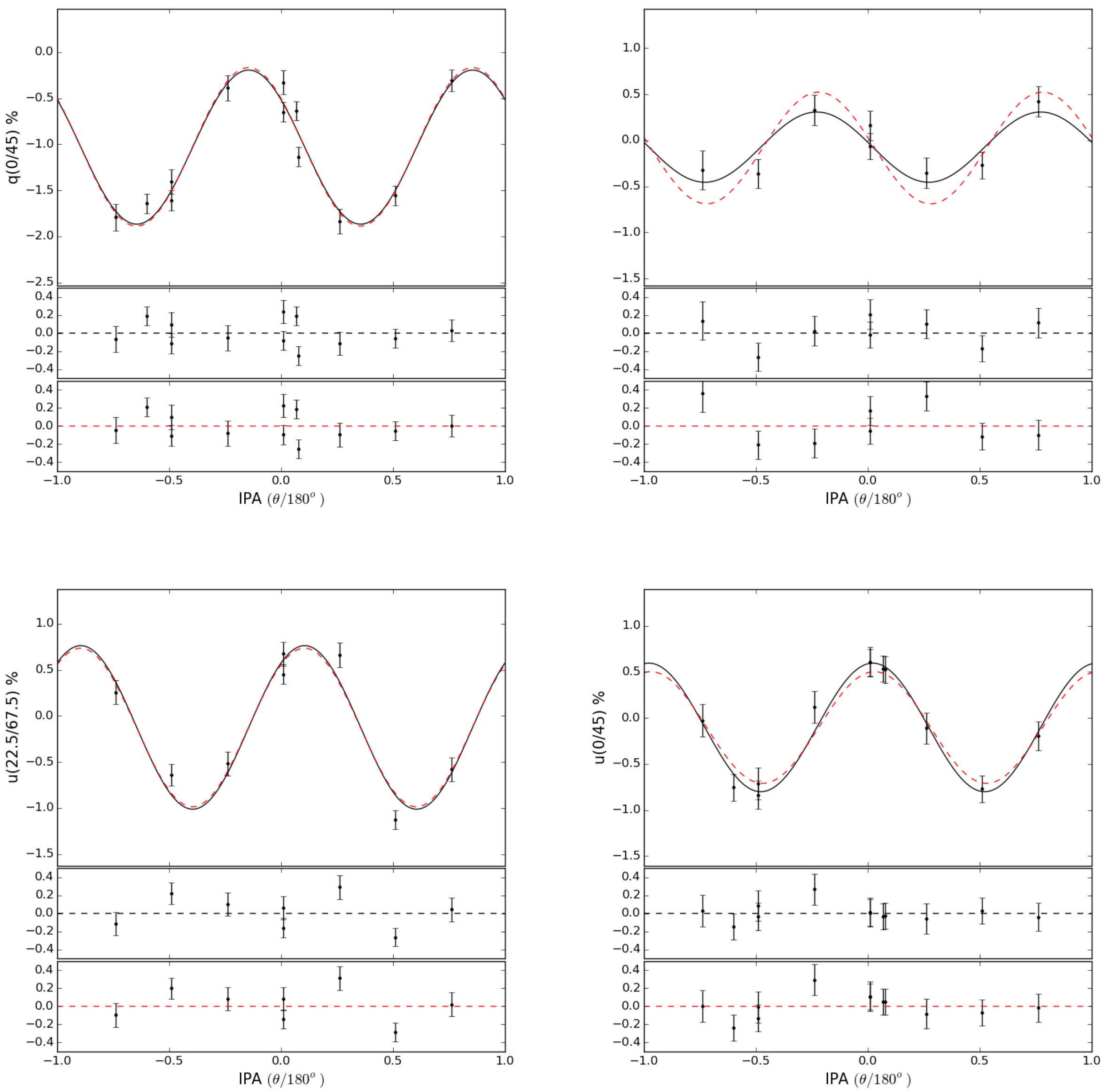

Figure 3: Instrumental polarization measurements with respect to IPA for H filter. Black line represent the variable amplitude fit and red line the constant amplitude fit

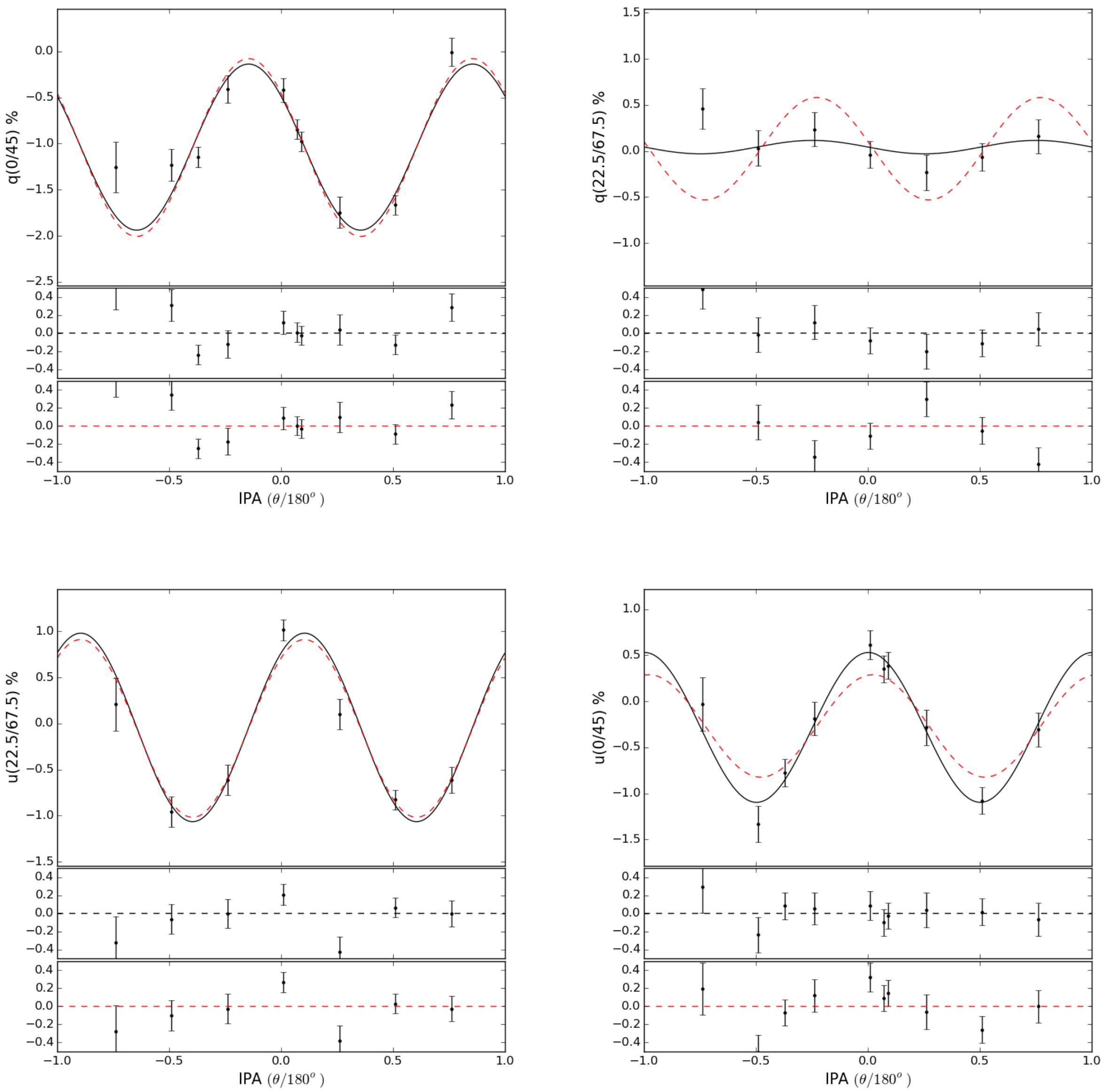

Figure 4: Instrumental polarization measurements with respect to IPA for J filter. Black line represent the variable amplitude fit and red line the constant amplitude fit

4 Polarized Standards

We observed two polarized standards from the catalog of Whittet et al, 1992 during commissioning time where IPA was set to -88 degrees and rotator tracking was on. We determine polarization degree of Schulte24 with χ^2 values of 0.93, 1.53 and 1.12 (or RMS values of 0.24, 0.23, 0.31) respectively for K_s, H, and J filters. In the field of Schulte 25, there is a nearby bright star which is not previously reported. Therefore, polarization measurements for Schulte 25 may not be compatible with the one in the catalog and should be avoided for future observations. In addition, they report K band results with a non-standard blue filter.

For each measurement, we report the rotator angle (ROT), deviation in the rotation angle (ΔROT), polarization degree ($p = \sqrt{q^2 + u^2}$), uncalibrated polarization angle ($\theta_0 = 0.5 \arctan(u/q)$) and calibrated polarization angle (see Section 4.3). Measurement errors include photometric errors, systematic calibration errors and uncertainty in the rotator angle.

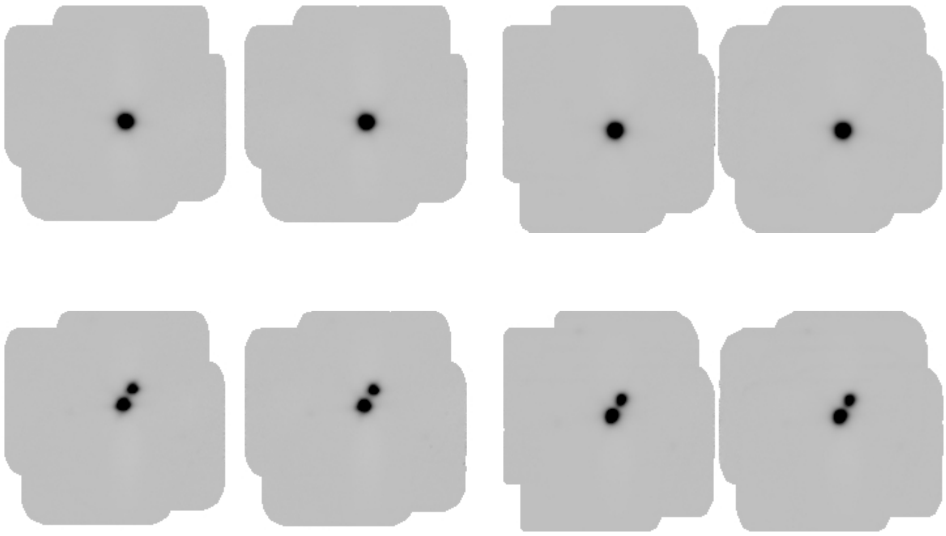

Figure 5: K_s band images of Schulte 24 and 25 (top and bottom) taken with HWP at 0°. Five point dither images are combined each with 100 sets of 100 ms exposures.

4.1 Schulte 24

20 33 17.482 +41 17 09.31
J=8.4 mag(1.36%(0.03) at 66^o(1))
H=7.9 mag(0.89%(0.03) at 65^o(2))
K_s=7.6 mag(0.43%(0.16) at 84^o(13))

Filter	ROT	ΔROT	p(%)	θ_o	θ_s
Ks	-72	6.0	0.61(0.27)	-11.3(19.9)	80.3
Ks	-150	3.0	1.01(0.21)	-27.6(12.0)	96.6
Ks	-48	4.0	0.50(0.21)	0.6(24.2)	68.4
Ks	-1	1.0	0.47(0.20)	3.7(24.2)	65.3
Ks	-180	2.0	0.48(0.20)	-0.1(23.5)	69.1
Ks	-72	6.0	0.28(0.28)	-6.9(41.9)	75.9
Ks	-8	2.0	0.41(0.20)	10.4(27.6)	58.6
	Mean(p, θ)		0.55	-12.3	81.3

Filter	ROT	ΔROT	p(%)	θ_o	θ_s
H	-63	10.0	0.81(0.31)	18.0(19.2)	51.0
H	-147	3.0	0.77(0.19)	-20.2(14.1)	89.2
H	-44	4.0	0.57(0.19)	17.8(19.6)	51.2
H	0	1.0	0.53(0.18)	5.6(19.1)	63.4
H	-66	6.0	1.14(0.25)	5.6(9.8)	63.4
H	-6	2.0	0.75(0.18)	2.9(13.6)	66.1
	Mean(p, θ)		0.72	2.8	66.2

Filter	ROT	ΔROT	p(%)	θ_o	θ_s
J	-55	4.0	0.80(0.32)	22.0(22.6)	47.0
J	-144	3.0	1.04(0.31)	-16.8(17.0)	85.8
J	-39	4.0	1.41(0.31)	10.5(12.6)	58.5
J	1	1.0	1.39(0.31)	10.6(12.4)	58.4
J	-59	6.0	1.19(0.35)	0.3(15.0)	68.7
J	-5	2.0	1.55(0.30)	8.0(11.1)	61.0
	Mean(p, θ)		1.24	6.0	63.0

4.2 Schulte 25

20 33 25.564 +41 33 27.00
J=8.2 mag(1.71%(0.04) at 66^o(1))
H=7.7 mag(1.10%(0.02) at 64^o(1))
K_s=7.5 mag(0.55%(0.1)at 76^o(7))

Filter	ROT	ΔROT	p(%)	θ_o	θ_s
Ks	-7	1.0	0.62(0.20)	-2.8(18.8)	71.8
Ks	-156	2.0	0.75(0.21)	-14.6(15.5)	83.6
Ks	5	1.0	0.54(0.21)	0.2(21.6)	68.8
	Mean(p, θ)		0.64	-7.5	76.5

Filter	ROT	ΔROT	p(%)	θ_o	θ_s
H	-6	1.0	0.87(0.19)	4.3(12.1)	64.7
H	-154	3.0	0.72(0.20)	1.4(14.8)	67.6
H	6	1.0	0.66(0.19)	2.7(15.8)	66.3
	Mean(p, θ)		0.75	3.0	66.0

Filter	ROT	ΔROT	p(%)	θ_o	θ_s
J	-4	1.0	1.30(0.31)	2.7(13.5)	66.3
J	-152	3.0	0.98(0.32)	6.1(17.9)	62.9
J	7	1.0	0.90(0.31)	0.9(19.5)	68.1
	Mean(p, θ)		1.06	3.2	65.8

4.3 CIRCE Polarization Angle Offset

We compare our polarization angle measurements with the catalog values and we obtain offset of the polarization angle as $69^\circ \pm 3^\circ$ degrees. Errorbars represent the combination of the catalog and our measurement errors. Polarization angles observed with CIRCE rotates in the opposite direction of the standard definition, therefore, real values can be obtained by $\theta_s = 69^\circ \pm 3^\circ - \theta_o$.