

## Extended Commissioning and Calibration of the Dual-Beam Imaging Polarimeter

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**Abstract.** In our previous paper (Masiero et al. 2007) we presented the design and initial calibrations of the Dual-Beam Imaging Polarimeter (DBIP), a new optical instrument for the University of Hawaii's 2.2 m telescope on the summit of Mauna Kea, Hawaii. In this followup work we discuss our full-Stokes mode commissioning including crosstalk determination and our typical observing methodology.

### 1. Introduction

To study the linear polarization of asteroids and other point source objects, the Dual-Beam Imaging Polarimeter (DBIP) was commissioned in March of 2007 (Masiero et al. 2007). In August of 2007 we expanded DBIP's capabilities to include analysis of circular polarization with the addition of a quarterwave plate. Typically, the most important quantities for analysis are the fractional polarizations  $q = Q/I$ ,  $u = U/I$ , and  $v = V/I$ , expressed as percentages, and in the following text we will deal with these quantities when we refer to polarization measurements. Here we present our subsequent calibration and determination of systematic errors which were found to be comparable to statistical errors for typical observing situations:  $\sim 0.1\%$  polarization.

### 2. Optical Setup

The original setup of DBIP was a serial arrangement of a halfwave plate in an encoded rotation stage, a filter and a double-calcite Savart plate placed between the telescope and the  $2k \times 2k$  Tektronix CCD camera. To extend DBIP to full-Stokes sensitivity, a quarterwave plate in a rotation stage was placed ahead of the halfwave plate. This setup allows for simultaneous measurement of linear and circular polarization, though at the potential cost of increased crosstalk between polarizations, which is discussed further in §3.3. Figure 1, modified from Masiero et al. (2007), shows a schematic representation of the new optical path with the quarterwave plate added.

### 3. Calibration

As with any optical system, misalignments and imperfections in the components will lead to errors in measurement. In the case of DBIP, the waveplates are

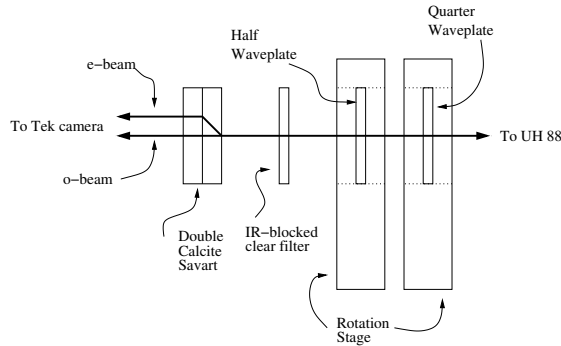


Figure 1. Schematic of the optical components of DBIP. Modified from Masiero et al. (2007).

the most sensitive components to these errors, as they are the only moving parts and require precisely determined angular zero-points. Errors in angular alignment of the waveplate or tilt with respect to the optical axis as well as chromatic retardance or fast-axis angle variations will show up in our system as variations in measured position angle of polarization, depolarization of the signal, or crosstalk between linear and circular polarization. To minimize and quantify these errors we performed an extensive calibration campaign.

### 3.1. Waveplate Alignment

Our first step of calibration was to determine the alignment of the waveplate zero-points using known standard stars. Having already aligned the halfwave plate against standards before the installation of the quarterwave plate (Masiero et al. 2007), we were able to re-observe one of the same polarization standards (NGC 2024-1) in full-Stokes mode to align the quarterwave zero-point while confirming that we could reproduce the linear polarization results for this target. The set of observations of NGC 2024-1, both before and after the addition of the quarterwave plate, are listed in Table 1, where a circular polarization value of “—” indicates a measurement taken before the installation of the quarterwave plate.

Table 1. Polarized Standard Star Observations

Name	Obs Date	% Lin Pol <sub>lit</sub>	$\theta_{lit}$	% Lin Pol <sub>obs</sub>	$\theta_{obs}$	% Circ Pol <sub>obs</sub>
BD-12 5133	3/24/07	$4.37 \pm 0.04$	$146.84 \pm 0.25$	$4.26 \pm 0.01$	$146.20 \pm 0.10$	—
NGC 2024-1	3/24/07	$9.65 \pm 0.06$	$135.47 \pm 0.59$	$9.70 \pm 0.02$	$136.11 \pm 0.05$	—
NGC 2024-1	1/17/08	$9.65 \pm 0.06$	$135.47 \pm 0.59$	$9.68 \pm 0.04$	$135.78 \pm 0.12$	$-0.04 \pm 0.04$
NGC 2024-1	3/12/08	$9.65 \pm 0.06$	$135.47 \pm 0.59$	$9.65 \pm 0.02$	$135.75 \pm 0.05$	$0.12 \pm 0.02$
BD-13 5073	5/14/08	$3.66 \pm 0.02$	$152.55 \pm 0.11$	$4.62 \pm 0.05$	$149.28 \pm 0.31$	$0.07 \pm 0.05$
BD-12 5133	5/14/08	$4.37 \pm 0.04$	$146.84 \pm 0.25$	$4.30 \pm 0.05$	$146.26 \pm 0.31$	$-0.04 \pm 0.05$
BD-12 5133	6/11/08	$4.37 \pm 0.04$	$146.84 \pm 0.25$	$4.29 \pm 0.03$	$145.17 \pm 0.21$	$0.02 \pm 0.03$
VI Cyg 12	6/11/08	$8.95 \pm 0.09$	$115.00 \pm 0.30$	$8.69 \pm 0.04$	$116.04 \pm 0.13$	$-0.16 \pm 0.04$

Table 2. Unpolarized Standard Star Observations

Name	Obs Date	% Lin Pol <sub>lit</sub>	% Lin Pol <sub>obs</sub>	$\theta_{obs}$	% Circ Pol <sub>obs</sub>
HD 64299	03/23/07	$0.15 \pm 0.03$	$0.10 \pm 0.01$	$83 \pm 4$	—
WD 1615-154	03/24/07	$0.05 \pm 0.03$	$0.02 \pm 0.02$	—	—
WD 1615-154	03/12/08	$0.05 \pm 0.03$	$0.04 \pm 0.03$	—	$-0.01 \pm 0.03$
WD 1615-154	05/14/08	$0.05 \pm 0.03$	$0.02 \pm 0.03$	—	$0.08 \pm 0.03$
WD 1615-154	06/11/08	$0.05 \pm 0.03$	$0.19 \pm 0.06$	$158 \pm 9$	$0.05 \pm 0.06$
BD+28d4211	08/29/07	$0.05 \pm 0.03$	$0.02 \pm 0.02$	—	$0.00 \pm 0.02$
WD 2149+021	08/30/07	$0.04 \pm 0.01$	$0.03 \pm 0.02$	—	$0.00 \pm 0.02$
G191B2B	01/17/08	$0.06 \pm 0.04$	$0.02 \pm 0.03$	—	$0.01 \pm 0.03$

### 3.2. Instrumental Polarization

In order to test for instrumental polarization or depolarization, we have observed polarized and unpolarized standard stars over a 15 month baseline. Tables 1 and 2 give our measured polarizations and position angles for polarized and unpolarized standard stars, respectively, as well as literature values for these objects from Fossati et al. (2007), Schmidt, Elston, & Lupie (1992) and the Keck/LRISp standards<sup>1</sup>. Our measurements for both polarized and unpolarized standards agree within  $3\sigma$  of the literature values, confirming that instrument systematics are less than a 0.1% effect. The only exceptions to this are the observations of BD-13 5073 and WD 1615-154. BD-13 5073 clearly shows evidence of variation in the amplitude and direction of polarization from the literature values over only a few years, showing it cannot be depended upon as a polarized standard. Our observation of WD 1615-154 on 6/11/08 shows anomalously high polarization compared to literature values and our previous observations at the  $\sim 3\sigma$  level. With the current data it is unclear if the polarization properties of the object have changed or if this measurement is just an outlier.

### 3.3. Crosstalk

Instrumental crosstalk between Stokes vectors is one of the more subtle errors that can affect polarization measurements and quantifying its magnitude is a critical step toward obtaining high precision polarimetry. Crosstalk between linear Stokes vectors ( $Q$  to  $U$  or  $U$  to  $Q$ ) happens when the zero-point location of the halfwave retarder is offset from the defined  $Q$  direction, and is easily corrected by aligning the waveplate, as discussed above in §3.1. Crosstalk from circular to linear and back ( $V$  to  $Q&U$  or  $Q&U$  to  $V$ ) can be caused by waveplate offsets or by variations in retardance of the wave-plates as a function of wavelength, position on the plate, etc.

To fully determine the instrumental crosstalk, light with a known polarization must be sent through the instrument and measured upon exiting. It is possible to do this by installing polarizers just in front of the instrument during observations (recent examples include Perrin, Graham, & Lloyd 2008; Snik et al. 2006, etc.), however due to limited observing time and space in the optical path

<sup>1</sup><http://www2.keck.hawaii.edu/inst/lris/polarimeter/polarimeter.html>

this was not a feasible calibration method for DBIP. Instead, we performed lab bench calibrations to quantify instrumental crosstalk.

To measure  $Q&U$  to  $V$  crosstalk we sent a collimated light source through a linear polarizer into DBIP and measured one of the two exiting beams with a precision photodiode. By stepping the angular position of the input linear polarizer, we were able to fully characterize this linear-to-circular crosstalk. To measure  $V$  to  $Q&U$  crosstalk a fixed quarterwave plate was installed after the linear polarizer. By stepping the linear polarizer again, we were able to vary the input polarization from circular to linear and back and characterize this circular-to-linear crosstalk.

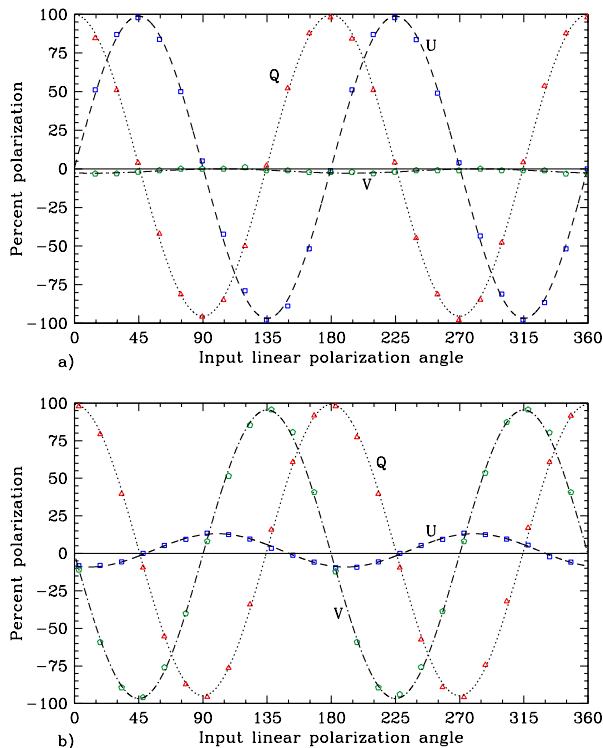


Figure 2. Polarization crosstalk measurements for DBIP for two cases: (a) for input of pure linear polarization rotated through 360 degrees, and (b) for input of rotated linear polarization passed through a fixed quarterwave plate. Sinusoids for both cases were fitted using a chi-squared minimizer, and are labeled with the Stokes vectors they represent.

Figure 2 shows our measured polarization state for both setups as the input linear polarizer was stepped through 360 degrees. Sinusoids describe the behavior of the polarization vectors in both setups and were fit with a chi-squared minimizer to the data to determine percentage crosstalk as well as any depolarization from the optics. We find that the circular polarization measured when inputting pure linearly polarized light had an amplitude of 1.4% and an offset of  $-1.4\%$ , with crosstalk preferentially occurring when both  $Q$  and  $U$  are positive

(around  $22^\circ$  on our plot). We measure a depolarization of both linear signals varying from  $< 0.5\%$  near  $22^\circ$  to  $\sim 4\%$  near  $112^\circ$ . Since these crosstalk errors are only a few percent of the input signal, for sources with “typical” polarizations (i.e.  $5 - 10\%$ ) the crosstalk error is comparable to the desired statistical errors of  $\sim 0.1\%$  polarization, as we measured for our polarized and unpolarized standards.

For the measurement of circular-to-linear crosstalk, we find a small amount of linear  $u$  polarization generated from a purely circularly polarized input beam, preferentially when  $+v$  is input. Note that the phased oscillation of  $q$  and  $u$  indicate a small misalignment of the quarterwave plate axes with the instrument-defined  $Q$  orientation, while it is the slight phase offset between  $-u$  and  $+q$  that is produced by the crosstalk. We also see clear evidence for a depolarization of the circularly polarized signal at the level of  $\sim 4\%$  of the input polarization. For targets with total circular polarizations less than a few percent these errors should be comparable the  $0.1\%$  noise error typically obtained in our observations.

#### 4. Conclusion

We have presented the results of our extended commissioning of DBIP into full-Stokes mode. Crosstalk values are shown to be small and can be ignored for objects with “typical” (i.e.  $< 5\%$ ) polarizations. With errors well constrained DBIP is now available for scientific studies of linear and circular polarization of point sources in the optical. DBIP has already been successfully used to characterize the polarization-phase curves of asteroids with some of the most pristine compositions in the inner solar system (Masiero & Cellino 2008) and a number of other programs to study small solar system bodies are currently under way.

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