BeePol: an imaging polarimeter for the Farid & Moussa Raphael Observatory

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Abstract. BeePol is an imaging polarimeter designed for the 60-cm telescope of the Farid & Moussa Raphael Observatory (FMRO) at Notre Dame University Louaize (NDU). It is based on the use of a Wedged Double Wollaston prism (WeDoWo), allowing for the simultaneous measurement of the I, Q, and U stokes parameters. When coupled to an Apogee Alta F42, 2k × 2k back illuminated, thinned, CCD camera, the polarimetric module allows for polarimetric imaging of a 1.25' × 10' field of view. Calculations done for the observing conditions at the FMRO show that the instrument may detect 1% polarization at 3σ for objects of magnitude 9, with an integration time of 1 hour. BeePol aims to serve as the prototype for an inexpensive imaging polarimeter of interest to small observatories. This paper reports on the basic design of the instrument, and ongoing work to build, test it, and start science observations.

1. Introduction
The FMRO, described in [1], is a small campus observatory with photometric and spectroscopic capabilities. The observatory’s most important use is for education, and for research in observational astrophysics. We wished to explore the possibility to measure all properties of light by adding polarimetry to the range of possible observational projects that may be carried at the FMRO. One of the primary use of polarization in astronomy is related to the determination of magnetic fields in various astrophysical media. Polarization of background stars by aligned dust grains serves to determine field properties in large interstellar clouds, an important parameter in understanding star formation. Furthermore, polarization as a function of wavelength affords information about dust properties in various media, such as cometary tails, interstellar and circumstellar environments. Polarization is also used to reveal information about the geometries of scattering media in unresolved objects. With the advent of CCDs, 2-D polarization measurements where introduced, mainly for extended objects or the simultaneous measurements of multiple stars in fields. Imaging polarimetry allowed for detailed studies of comets, galaxies, and reflection nebulae, mostly around YSOs, among other. In order to introduce some of the different possible studies to the capabilities of the FMRO, we decided to design and build a small polarimetric module we called BeePol. It is meant to be based on the simplest possible design with, as much as possible no moving parts, and using off the shelf parts to the maximum extent possible. In what follows we describe BeePol, and the science that may be possible with the instrument installed at the FMRO telescope. Section 2 described the basic...
layout of BeePol, section 3 discusses the limitations set by the proposed set-up, and identifies possible targets, and we conclude with a brief description of ongoing work to build BeePol.

2. Design of BeePol

BeePol is based on the IMPOL polarimeter [2]. We have replaced the rotating half-wave plate and the Wollaston prism by a wedged double Wollaston (WeDoWo) as described by Oliva [3]. With a WeDoWo, one obtains simultaneous non-overlapping polarized images of the field of view (FOV) at each of $0^\circ$, $45^\circ$, $90^\circ$, and $135^\circ$ position angles. This allows for the simultaneous calculation of the first three stokes parameters, $I$, $Q$, and $U$. Linear polarization is thus instantaneously determined in the FOV. Figure 1, from [3] shows the principle of operation of the WeDoWo.

![Figure 1. The basic principle of operation of the WeDoWo in imaging and spectropolarimetry, figure from [3]](image)

The basic optical layout of BeePol is shown in figure 2. It uses two commercially available achromats as collimating and imaging lenses. The filter wheel was placed before the CCD, rather than before the module to account for the mechanical properties of its box and reduce flexure within the device. Based on the appropriate equations found in [3], we have calculated the field of view and prism angles of the We-Do-Wo. In view on available lenses, and the need to have a reasonable field of view, we have adopted a pupil size of 2.5 cm.

The polarimetric module will be used with the FMRO main imager, an Apogee Alta F-42 [5]. When installed at the 24-inch telescope, the camera provides for a scale of 0.68” per pixel. We have striven to preserve a similar plate scale when used with BeePol. The pixel size on
the sky was used as the main constraints to determine the field of view that will create four non-overlapping images on the CCD. BeePol will thus be able to measure polarization on a field of $1'15'' \times 10'$ in a single exposure.

3. Science with BeePol

BeePol is meant to be used on a small telescope. In order to assess its capability, we have computed the expected detection limits of the instrument when used at the FMRO. The uncertainty on a dual-beam polarimetric measurement is given by [6]

$$\sigma_P = \frac{1}{\sqrt{\frac{N}{2}}SNR}$$

where $N$ is the number of half-wave plate positions used. In our case, with a WeDoWo, $N = 1$. $SNR$ is the signal to noise ratio on the total intensity $I$. To determine the capabilities of BeePol, we have assumed that the detection limit is $3\sigma_P$. Furthermore, when calculating the exposure time from the $SNR$, we have assumed a seeing of 2", and a sky brightness of 18 mag/arcsec$^2$ in all filters (UBVRI). The equation used is:

$$SNR = \frac{n_e \times T \times QE \times t}{\sqrt{(n_e + n_{sky} \times N_{pix}) \times T \times QE \times t + (RN^2 + DC \times t) \times N_{pix}}}$$

where $n_e$ and $n_{sky}$ are the photon rates arriving at the telescope from the star and the sky background, respectively, $T$ the transmission of the optics, $QE$ the quantum efficiency of the detector, $RN$ and $DC$ the read noise and dark currents, $N_{pix}$ the number of pixels covered by the seeing disk, and $t$ the exposure time. Results are summarized in figure 3. Based on these expected performance indicators, the best targets should be bright and highly polarized. In that regard, the list of potential targets that may lend themselves to work with BeePol are:

- Comets at high enough phase angles;
- Bright YSOs and their associated reflection nebulae;
- Objects were mass loss and/or rotation produces highly non-spherical geometries such as post-AGB stars or WR+O binary systems.
One should also keep in mind that the interest of small telescopes resides in the availability of time, and thus in the ability to provide long-term monitoring of such objects.

4. Conclusion
We have presented the design of BeePol, a polarimetric imaging module designed for used on the 24-inch telescope of the FMRO. The design is based on the principle of a low-cost instrument that will allow for interesting polarization measurements. We are currently in the process of building and testing the instrument. Tests will first be performed on an optical bench. The module’s housing will be built at the workshops of NDU. It will then be tested on the telescope. We are aiming for first light in the summer of 2017.

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