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Automated Polarimetry with Smaller Aperture Telescopes: The ROVOR Observatory

Joseph Moody [1,*], Parkes Whipple [1], Lauren Hindmann [1], Nicholas Van Alfen [1], Jonathan Barnes [2], Nicolas A. Ducharme [1], L. Joseph Rivest III [1], McKay D. Osborne [1], Marcus Holden [3], Cameron Pace [4], Richard L. Pearson III [5], Bret Little [1] and Eric Hintz [1]

1 Department of Physics and Astronomy, Brigham Young University, Provo, UT 84602, USA; parkes.whipple@gmail.com (P.W.); lauren.hindman1@gmail.com (L.H.); nvanalfen2@gmail.com (N.V.A.); nicolas.ducharme1@gmail.com (N.A.D.); ljrivest3@gmail.com (L.J.R.); mckayosborne.cn@gmail.com (M.D.O.); bret.little@gmail.com (B.L.); eric_hintz@byu.edu (E.H.)

2 Salt Lake Community College, 4600 South Redwood Road, Salt Lake City, UT 84123, USA; jonathan.barnes@slcc.edu

3 Department of Engineering, University of Idaho, 995 University Blvd #225A, Idaho Falls, ID 83401, USA; makasuh@gmail.com

4 Department of Physical Science, Southern Utah University, Cedar City, UT 84720, USA; cameronpace@suu.edu

5 Department of Physics, Metropolitan State University of Denver, 890 Auraria Parkway, Denver, CO 80204, USA; richard.pearson@astronomy4kids.net

* Correspondence: jmoody@byu.edu; Tel.: +1-801-422-4347

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Abstract: To better understand possible blazar jet mechanisms and morphologies, brighter prototypical objects are regularly monitored for variability in optical broad-band light. If the monitoring filters are polarized, the position angles and polarization percentages can be measured and their evolution monitored over time. However, building up a statistically significant time base of polarization parameters requires the arduous task of monitoring sources for months or years to catch and follow interesting events such as flares. Fortunately, monitoring an object is easily done using remotely operated or robotic telescopes. The Remote Observatory for Variable Object Research (ROVOR) is a small-aperture telescope that has monitored blazars in broad-band Johnson filters since 2009. Calibration data using a set of four plane-polarized filters suggest that it is suitable for polarimetric monitoring as well. We have successfully collected data on CTA 102 and are encouraged at the prospects of monitoring it and other similar objects. Long-term monitoring campaigns are a scientifically and educationally-effective use of underutilized smaller-aperture telescopes.

Keywords: blazar; monitoring; polarization

1. Introduction

Astrophysical jets coming from the nuclei of active galaxies are laboratories for studying relativistic particles influenced by extremely strong magnetic fields. These jets give off diagnostic radiation spanning from radio to γ-rays. At optical wavelengths, broad-band blazar monitoring remains a cost-effective way of tracking general blazar behavior. Polarization monitoring is especially useful for the magnetic field information it contains and for how it can track the progress of ejecta traveling along field lines. A correlation between radio and optical polarization suggests that the sites of emission for both are at least partially coincident as well, illustrating how polarization monitoring helps our understanding of outflow structures [1,2].

Time and money economics, as well as science, dictate a monitoring cadence—especially at high and low energies best probed with large and expensive equipment. Fortunately, at optical wavelengths, the cost of setting up smaller-aperture optical telescopes as monitoring stations is not prohibitive and has actually decreased in the past decades to the point where an entire observatory can be set up for less than $100 k US dollars. While still not cheap, it does mean that several monitoring stations can be established for the cost of a typical research grant. Therefore, appropriate little-used telescopes have the potential for being converted into monitoring stations.

The cost of equipment is not the only consideration in establishing an optical monitoring program. The cost in time and labor is often greater. These costs are hard to estimate up-front in blazar research where success often depends on the unpredictable activity of a fickle target. If significant research results are a necessary outcome for program viability (as is reasonable to expect), monitoring is a risky business.

For educationally-oriented institutions, however, training students in the skills of astronomy is as valuable as research results. Such training should include some observational experience so students can at least appreciate the issues in gathering quality data. Providing training in observational astronomy is logistically challenging with classes during the day and observational research being conducted on weather-dictated evenings. For this reason, hands-on instruction in observational techniques has been limited to the infrequent times when both instructor and student can flexibly operate on a night-time schedule.

In light of this, the Remote Observatory for Variable Object Research (ROVOR) was established in 2009 to instruct undergraduate students in observational astronomy [3] without negatively impacting their daily routine. The school it serves, Brigham Young University (BYU), has one of the largest undergraduate physics and astronomy programs in the world, and needed an effective means of instructing its undergraduate astronomy majors during regular semesters. ROVOR is a remotely operated 0.4 m RCO telescope on a Paramount ME that is controlled over the internet. Located on a dark site 150 km south of the Provo Utah campus, it is operated every clear night via script by undergraduate students. Setup takes place during the day, the telescope performs all observations at night without operator assistance, and shuts down automatically at dawn. Over 30 students have been trained on it, while producing or contributing to approximately one refereed monitoring paper per year (e.g., [4–10]).

ROVOR is operated every semester by a team of approximately six undergraduate students. The most senior student organizes and manages the team. The science program is determined by the faculty advisor. Scripting for observing is done at school on a dedicated computer and is shared to all team members and the remote telescope through *Dropbox* (San Francisco, CA, USA). The actual telescope control is done by remotely communicating with the on-site computer. This communication can be done through laptops or tablets so experienced students often operate from their homes. Data are transferred to BYU every morning using a file-transfer-protocol (ftp) program.

Data at BYU are processed through a semi-automatic reduction pipeline. Each research project has a student head who writes or uses software written specifically for that project. As one example, spreadsheet-based software was developed by a student to accept standard star and object photometry from *IRAF* as part of a broad-band blazar monitoring program and automatically calibrate and plot it with previous results. This way, the students see results immediately, helping them relate to and stay engaged with the science.

Motivated by requests within the Whole Earth Blazar Telescope (WEBT) [11] community for more polarimetric data, we installed four plane-polarized filters on the ROVOR telescope in the fall of 2016 and repurposed it to monitor polarization as well as photometry. Our goal was to produce data similar to that from institutions such as Boston University and St. Petersburg State University [12,13], as well as the RoboPol collaboration [14]. We are especially interested in monitoring brighter ($V < 15$) blazars during quiescent times, since these epochs are often less observed. Such data will support and compliment monitoring activities like the VLBA-BU-BLAZAR, RoboPol and GASP-WEBT programs.

2. System Calibration

The filter wheel at ROVOR is a Fingerlakes Centerline with two separate five filter wheels. The plane-polarized filters were installed in one wheel. The first filter was positioned to allow maximum transmission for polarized light oriented N–S. The plane of maximum transmission for the subsequent filters was rotated eastward by 45, 90, and 135°, respectively. A Johnson broadband set was installed in the other wheel. In principle, this arrangement can measure polarization in all Johnson bands. We limited our observations to finding polarization percentages and position angles (PAs) through the V filter.

We calibrated this system using Serkowski standard stars recommended for the Subaru FOCAS instrument [15–17]. For unpolarized standards, we used GD 319, HD 154892, BD+32d3739, BD+28d4211, and HD 212311. For polarized standards we used BD+64d106, HD 251204, VI Cyg #12, and HD 204827.

Polarization standards were observed on eight photometric nights spread over 6 weeks. The nights were 10, 12, 14 April and 10, 11, 13, 29, and 30 May 2017. Occasionally, the same standard star was observed twice in one night. All observations were completed in sets of three through each polarization orientation, and the results were averaged. The signal-to-noise ratio for each data point in each polarization orientation was never less than 240. Relevant data are in Table 1.

Table 1. Polarization standard observations.

Object	Exposure	Obs	Meas. Pol. (%)	(Stand. - Meas.) Pol. (%)	Meas. PA(°)	(Stand. -Meas.) PA(°)
BD+64d106	3 × 22 s	10	4.9 ± 0.29	−0.79	97.6 ± 1.6	1.1
HD 251204	3 × 20 s	10	4.5 ± 0.66	+0.41	146.6 ± 1.5	0.4
VI Cyg #12	3 × 60 s	5	8.8 ± 0.10	−0.20	115.0 ± 2.5	0.0
HD 204827	3 × 3 s	5	5.9 ± 0.33	−0.54	58.1 ± 1.3	0.6

In Table 1, the standard star ID is in column 1. Column 2 lists the exposure times. All observations were three exposures in each filter for 3 to 60 s, depending on the magnitude of the star. The total number of independent sets of observations are listed in column 3. The measured polarization percentage and its uncertainty is in column 4. The uncertainty is the standard deviation of the independent observations, and is expressed in percentage of polarization. The difference between the catalogued standard polarization and the measured polarization is in column 5. Column 6 gives the measured position angle and its standard deviation in degrees. Polarization percentage and position angles were determined by fitting a sine function through the angular sequence of polarization measurements using a Bayesian non-linear least-squares fitting procedure.

Our position angle data are transformed to the standard system [15] by a linear transformation. The fit of this relation is extremely accurate, with an R^2 value of 0.9997 (for reference, an R^2 value of 1.0 means the data are fit perfectly by a line with no residual error). In other words, the PA values transform to the standard system with essentially no uncertainty in the transformation itself.

Regarding unpolarized standards, each of these was observed between five and ten times in sets of three, as with the polarized standards. In all cases, the upper limit on polarization was below 0.3 percentage points. We conclude from the unpolarized data that our system is capable of measuring polarization to about 0.3 percentage points on high signal-to-noise data. From the polarized data, we conclude that (1) our system is capable of referencing data back to the standard system with an accuracy of approximately 0.5 percentage points, and (2) the uncertainty in position angle determinations is less than one degree.

3. First Results and Discussion

The ROVOR polarimetry capabilities have not yet been in place long enough to mount a monitoring campaign. However, we did observe polarization changes for CTA–when it was flaring at the end of 2016 and the beginning of 2017–which data are given in Table 2.

Table 2. Polarization of CTA 102. JD: Julian date; UT: Universal Time.

Date	JD	Magnitude (V)	Polarization (%)	PA (°)
17 December 2016	2,457,740.581	13.39	3.6 ± 0.8	140 ± 8
16 January 2017	2,457,770.609	13.47	8 ± 3	105 ± 15
17 January 2017	2,457,771.610	13.02	14 ± 2	100 ± 15

Columns 1 and 2 give the Universal Time (UT) date and Julian date (JD) of observation. These observations were taken in sets of five 60-s exposures through each polarization orientation. The typical signal-to-noise ratio was just over 100 for a single observation. Column 3 gives the Johnson V-band magnitude, column 4 gives the polarization percentage and uncertainty, and column 5 gives the PA and its uncertainty. These uncertainties are the RMS of the individual observations. Calibration was done by observing the polarization standard VI Cyg #12 before and after CTA 102.

The RMS scatter in these values is greater than the system uncertainty found from the polarization standards, meaning that some of the variance is intrinsic to the object. This demonstrates that ROVOR is capable of accurately measuring polarimetric changes in this object and others like it. While the correlation between magnitude and polarization in the table is not a new discovery, the rapid change in polarization magnitude between 16 and 17 January illustrates the need to monitor polarization on a rapid cadence to better understand the time-scales of change.

There are two main points to be made from this study:

(1) Retrofitting smaller telescopes with apertures <0.5 m to monitor the polarization of brighter blazars will more rapidly advance this science. (2) Such monitoring programs are an excellent way to train new students.

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Author Contributions: J.M. and J.B. conceived of the ROVOR observatory and built it with considerable assistance from C.P., R.L.P., and B.L. Polarimetric data were obtained by P.W. and J.M. with assistance from L.H., N.V.A., and N.A.D. Data analysis was accomplished by P.W. and J.M. with assistance form E.H., L.J.R., M.H., and M.D.O. This paper was written by J.M.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BYU	Brigham Young University
ftp	filte transfer protocol
JD	Julian Date
PA	Position Angle
RMS	Root Mean Square
ROVOR	Remote Observatory for Variable Object Research
UT	Universal Time
WEBT	Whole Earth Blazar Telescope

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