# Long-term monitoring of TeV Blazars with the Watcher Robotic Telescope

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**Abstract.** Blazars are known to show large-scale multi-wavelength variability on the order of sub-hours to years. This variability often manifests as rapid flares that can show correlation over a broad wavelength range. Since flares happen suddenly, rapid follow-up observations must be scheduled if a more detailed multi-wavelength observation campaign is to be started. We report on the long term optical photometric monitoring of a selection of known TeV blazars observed with the Watcher Robotic Telescope since May 2015 in the V, R and i' filters and present results of five well known sources: PKS 1510-089; AP Librae; PG 1553+113; PKS 2005-489 and PKS 2155-304. A reduction pipeline is currently in development to help identify potential sources for rapid follow-up multi-wavelength observations and provide optical light-curves to complement multi-wavelength observations. During the observation period PKS 1510-089 showed two outbursts and a $\Delta m_V = 1.7$ mag. Analysis with the Discrete Correlation Function between optical and $\gamma$-rays for PKS 1510-089 showed that all the flares are well correlated, suggesting a common origin for the optical and $\gamma$-ray emission. PKS 2155-304 showed a $\Delta m_V = 1$ magnitude difference and a steady increase in magnitude. PG 1553+113 exhibits an outburst with a total magnitude change of $\Delta m_V \sim 0.6$, while PKS 2005-489 shows a general magnitude increase toward the middle of the campaign and a decrease toward the end. No flare events were observed for AP Librae.

## 1. Introduction

Blazars are a class of Active Galactic Nuclei (AGN) which have a jet orientation which lies very close to the observer‘s line of sight ($\lesssim 10°$) and they can be subdivided into Flat Spectrum Radio Quasars (FSRQ) and BL Lacertae objects (BL Lac). BL Lacs and FSRQs are characterized by their rapid multi-wavelength variability on the order of sub-hours to years, high polarization (radio to optical) and highly Doppler boosted emission from the jet. The Spectral Energy Distribution (SED) of blazars show a “double-humped” profile, with the low energy component (radio to UV/X-ray) produced by synchrotron radiation and high energy component (X-ray to $\gamma$-ray) produced by inverse Compton (IC) emission in the leptonic scenario [1] [2]. There is still some debate as to the origin of the high energy component, whether leptonic, hadronic or lepto-hadronic (see e.g. [3], [4] or [5]).

The Watcher Robotic Telescope, situated at the Boyden Observatory, South Africa is currently undertaking long-term observation of a selection of blazars detected with the High Energy Stereoscopic System (H.E.S.S.) telescope. The observational campaign began in December 2014. We present light-curves for five of these sources: PKS 1510-089; AP Librae; PG 1553+113; PKS 2005-489 and PKS 2155-304, from May (MJD = 57154) to November (MJD = 57335) 2015 in the R, V and i' filters. In this short proceedings we analyse the long-term light-curves for these five sources to investigate their long-term variability. Aperture photometry was performed on *Fermi*-LAT ($0.1 \leq E_\gamma \leq 300$ GeV) data for PKS 1510-089 to investigate any correlation between its optical and $\gamma$-ray light-curves.

## 2. Data reduction pipeline and method

The goal of an automatic reduction pipeline is to reduce and analyse observational data with as little input by the user as possible. The reduction pipeline being developed in the `Python Programming Language` for the reduction of the Watcher Robotic Telescope data, uses output from various `Python` packages, such as `sep`, a module that uses `SExtractor` algorithms in `Python` to help analyse data [6], `pyRAF`, which allows `Python` programs to be executed in `IRAF` and `Astropy`, which reads the fits file headers during the `IRAF` reduction process [7] [8], allowing the pipeline to reduce long-term data with locally (daily) applicable bias, dark and flat files.

The reduction pipeline uses the output of the `Astropy` and `sep` modules as the input for `pyRAF`, which then performs the reduction and photometry with the standard `IRAF` `ccdred/ccdproc` and `daophot/phot` tasks. To ensure the quality of the data being reduced, the `sep` module is used to analyse the quality of the data and extracted sources. Frames are rejected if the background counts and total background noise (rms) is more than twice the average of all the data. This allows anomalous frames to to be rejected, while still keeping the overall data quality approximately the same. Frames are also rejected if the eccentricity of the extracted sources are more than $e = 0.9$.

The data obtained from the Watcher Robotic Telescope was run through the reduction pipeline and photometric results obtained from the `daophot/phot` task. Differential photometry was performed using the method outlined in Everett and Howell [9]. The corrected magnitude is calculated by:

$$m = m_{\mathrm{obs}} - \left( \langle m_i \rangle - \frac{1}{M} \sum_{j=1}^{M} \langle m_i \rangle_j \right). \tag{1}$$

Here $m_{\mathrm{obs}}$ is the observed instrumental magnitude per frame. The average instrumental magnitude of the $N$ comparison stars, weighted by their variance, per frame is $\langle m_i \rangle$, $M$ is the total the number of frames and $\langle m_i \rangle_j$ is the average magnitude of the comparison stars on frame $j$. The uncertainty in the corrected magnitude is determined by:

$$\sigma = \sqrt{\sigma_*^2 + \sigma_{ens}^2} \tag{2}$$

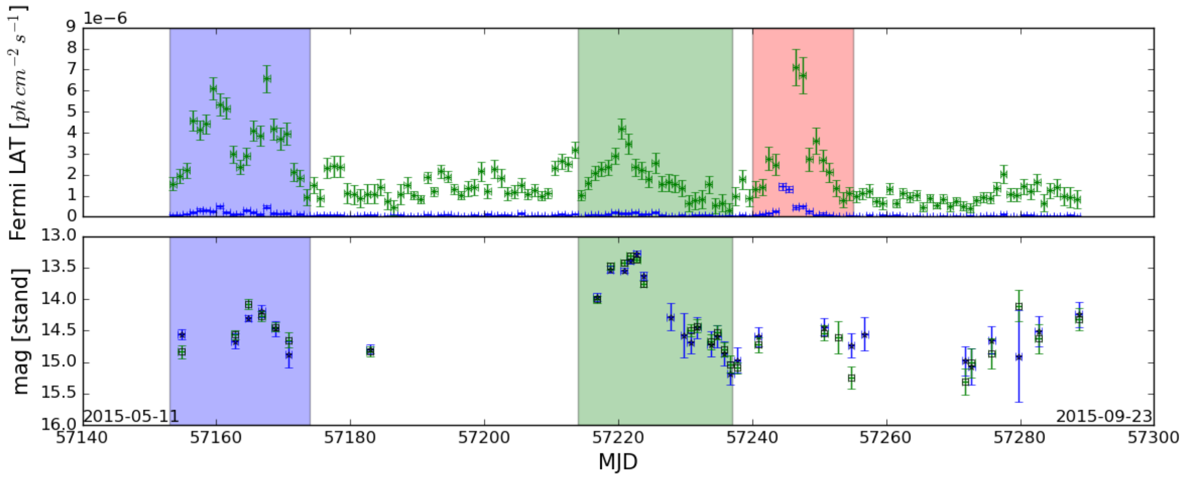
where $\sigma_*$ is the error calculated by `IRAF` for the star and $\sigma_{ens}$ is the ensemble error, given by

$$\sigma_{ens} = \left[ \sum_{i=1}^{N} \left( \frac{1}{\sigma_{*i}^2} \right) \right]^{-\frac{1}{2}} \tag{3}$$

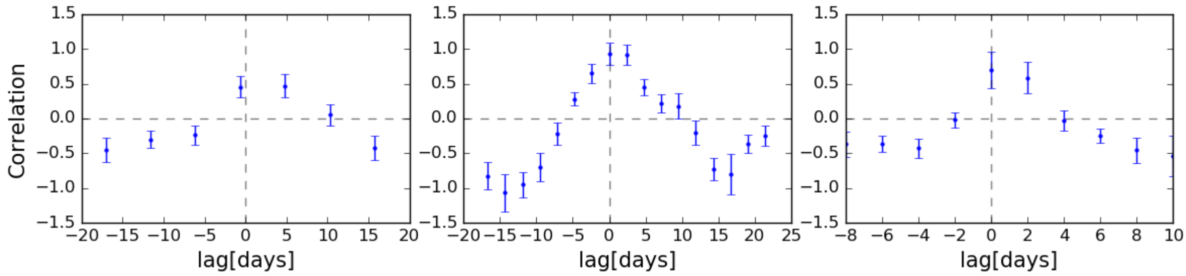
The Discrete Correlation Function (DCF) [10] was used to calculate correlations between the optical and $\gamma$-ray ($E_\gamma < 1$ GeV) flares in May and August 2015 and lower ($E_\gamma < 1$ GeV) and higher ($1 \leq E_\gamma \leq 300$ GeV) components of the flare detected by the LAT in August 2015 for PKS 1510-089.

## 3. Results and discussion

During the observation period PKS 1510-089 showed three flares detected in $\gamma$-rays, two of which were detected by the Watcher Robotic Telescope. The May 2015 flare was also detected




**(a)**




**(b)**

**Figure 1:** Light-curve and DCF for PKS 1510-089. Frame a) is the light-curve for PKS 1510-089. The top panel is the $\gamma$-ray light-curve from $E_\gamma < 1$ GeV (green crosses) and $1 \leq E_\gamma \leq 300$ GeV (blue plusses) emission. The green squares and blue stars are the R and V magnitudes respectively. Frame b) shows the correlations between the flares. Left and middle: May and July flares receptively. Correlations are calculated between $E_\gamma$ ($< 1$ GeV) emission and R filter, right: August flare. Correlations are between the ($1 \leq E_\gamma \leq 300$ GeV) and ($E_\gamma \leq 1$ GeV) $\gamma$-ray emission.

by M.A.G.I.C. (Major Atmospheric Gamma Imaging Cherenkov) [11] and the July flare was detected by the 0.6m telescope of the Belogradchik observatory, situated in Bulgaria [12]. The light-curve and DCFs for the three flares are shown in figure 1. The third flare was not observed by Watcher, but was detected in $\gamma$-rays by *Fermi*-LAT. The first flare, in May 2015, had a $\Delta m_V \approx 1$ magnitude change with a maximum daily $\gamma$-ray flux of $F(E_\gamma < 1\text{ GeV}) = (6.57 \pm 0.635) \times 10^{-6}$ ph cm$^{-2}$ s$^{-1}$.

The DCF calculations suggest a positive correlation with a lag of $\tau = 2.07 \pm 2.73$ days between the $E_\gamma < 1$ GeV emission and R filter. However, this $\sim 20$ day flare only has optical data every $\sim$ 4th day, so any information regarding short term correlation between the gamma-ray and optical emission should be treated with caution. The second flare in July 2015 showed a $\Delta m_V \approx$ 1.9 with a maximum daily $\gamma$-ray flux of $F(E_\gamma < 1\text{ GeV}) = (4.13 \pm 0.500) \times 10^{-6}$ ph cm$^{-2}$ s$^{-1}$. A DCF calculation showed a positive correlation with a $\tau = 1.19 \pm 1.19$ day lag between the $\gamma$-ray ($E_\gamma < 1$ GeV) emission and R filter. The third flare, in August, was not observed by Watcher, but a $\gamma$-ray flare was recorded with the LAT ($0.1 \leq E_\gamma \leq 300$ GeV). Maximum

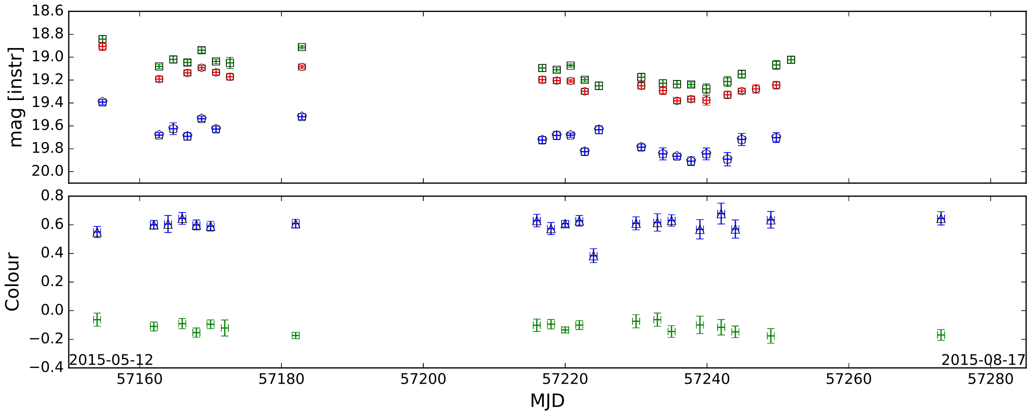



**Figure 2:** Light-curve for AP Lib. The light-curves show the data for the V(blue pentagons), R(green squares) and i'(red circles) filters in the top panels. The colour curves are shown in the bottom panels, with R-V(blue triangles) and R-i'(green plusses)

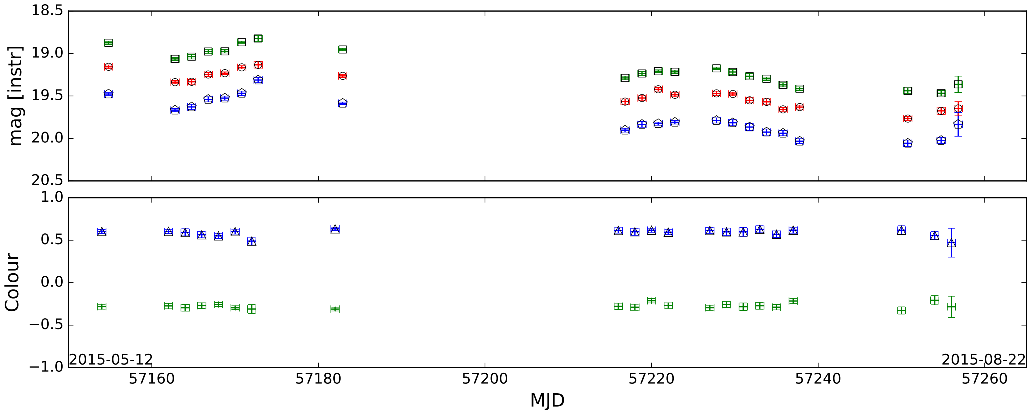



**Figure 3:** Light-curves for PG 1553+113. See figure 2 for description of symbols.

daily fluxes of $F(\mathrm{E}_\gamma < 1\ \mathrm{GeV}) = (7.125 \pm 0.864) \times 10^{-6}$ ph cm$^{-2}$ s$^{-1}$ and $F\ (\mathrm{E}_\gamma > 1\ \mathrm{GeV}) = (1.437 \pm 0.150) \times 10^{-6}$ ph cm$^{-2}$ s$^{-1}$ were recorded with the LAT. There was a lag of $\tau = 1 \pm 1$ days between the $1 \leq \mathrm{E}_\gamma \leq 300$ GeV and $\mathrm{E}_\gamma < 1$ GeV emission, calculated with the DCF.

AP Librae[1] showed a $\Delta m_V \approx 0.35$ magnitude change over the course of the observation campaign, with no sudden magnitude changes. Its R-V colour stayed constant ($\sim 0.6$), but its R-i' colour varied slightly around $\sim -0.1$. Its light-curve is shown in figure 2.

PG 1553+113 (figure 3) showed a overall decrease in magnitude with a $\Delta m_V \approx 1$ change. The R-V and R-i' colours stayed constant during the whole observation campaign with $\sim 0.6$ and $\sim -0.2$ respectively.

PKS 2005-489 showed a slight increase in magnitude toward the middle of the campaign, then a slight decrease toward the end, with an overall $\Delta m_V \approx 0.4$ magnitude change. The light-curve is shown in figure 4.

PKS 2155-304, shown in figure 5, displayed an overall magnitude increase during the campaign, with a $\Delta m_V \approx 1$ increase. It showed small variability ($\Delta m_R \approx 0.3$) in the R filter during the

[1] Please note that the instrumental magnitudes are used for AP Librae, PG 1553+113, PKS 20115-489 and PKS 2155-304.

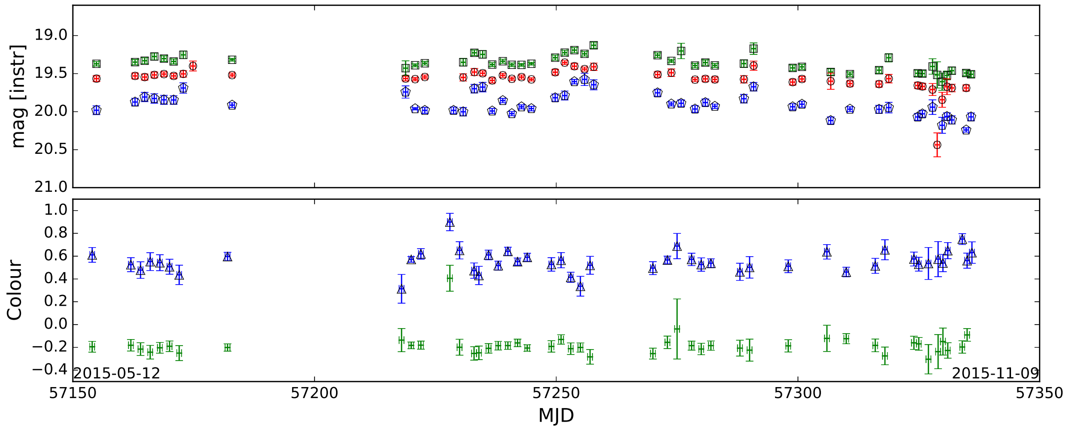



**Figure 4:** Light-curves for PKS 2005-489. See figure 2 for description of symbols.

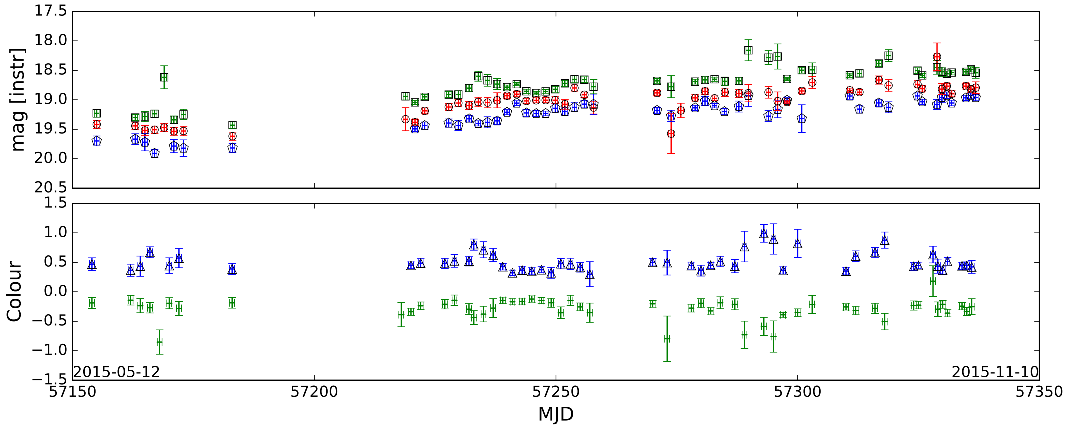



**Figure 5:** Light-curves for PKS 2155-304. See figure 2 for description of symbols.

middle of the campaign, but no corresponding change in magnitude was noted for the V and i' filters.

## 4. Conclusion

In this paper we presented light-curves on 5 well known TeV blazars observed with the Watcher Robotic Telescope for the period between May 2015 and November 2015. During this campaign, the FSRQ PKS 1510-089 ($z = 0.361$), which was discovered to be a TeV emitter in 2009 [13], experienced three flares during the observation period, two optical and $\gamma$-ray flares during May and July 2015 and a flare in August 2015 that was not detected by the Watcher Robotic Telescope, which was not observing the source during the flaring period. The August flare was detected *Fermi*-LAT in the $1 \leq E_\gamma \leq 300$ and $E_\gamma \leq 1$ GeV range.

AP Librae ($z = 0.049$), PG 1553+113 ($z = 0.43 - 0.58$); PKS 2005-489 ($z = 0.071$) and PKS 2155-304 ($z = 0.116$) are BL Lacs observed in the TeV range by H.E.S.S. [14]. The rapid flares of PKS 1510-089 hint that the emission during the flares originate from a small region in the jet and the small time lags between the $\gamma$-ray and optical emission has previously been shown to agree well with a Shock-in-Jet Model (see e.g. [15]). *Fermi*-LAT aperture photometry for AP Librae, PG 1553+113, PKS 2005-489 and PKS 2155-304 was also performed, but did not show any $\gamma$-ray variability flaring events. The automatic reduction pipeline, currently in development, used to reduce the data and perform photometry, gave reasonable results, although more development and testing, under different conditions, still needs to be carried out. A more rigorous $\gamma$-ray analysis still need to carried out on the flares detected by the *Fermi*-LAT to explore the emission regions and conditions during the flares. The preliminary results show the importance of long-term monitoring and the rigorousness of the reduction pipeline.

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