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Optimal strategies for observation of active galactic nuclei variability with Imaging Atmospheric Cherenkov Telescopes

Matteo Giomi*, Lucie Gerard, Gernot Maier

Deutsches Elektronen-Synchrotron DESY, Zeuthen D-15738, Germany

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ABSTRACT

Variable emission is one of the defining characteristic of active galactic nuclei (AGN). While providing precious information on the nature and physics of the sources, variability is often challenging to observe with time- and field-of-view-limited astronomical observatories such as Imaging Atmospheric Cherenkov Telescopes (IACTs). In this work, we address two questions relevant for the observation of sources characterized by AGN-like variability: what is the most time-efficient way to detect such sources, and what is the observational bias that can be introduced by the choice of the observing strategy when conducting blind surveys of the sky. Different observing strategies are evaluated using simulated light curves and realistic instrument response functions of the Cherenkov Telescope Array (CTA), a future gamma-ray observatory. We show that strategies that makes use of very small observing windows, spread over large periods of time, allows for a faster detection of the source, and are less influenced by the variability properties of the sources, as compared to strategies that concentrate the observing time in a small number of large observing windows. Although derived using CTA as an example, our conclusions are conceptually valid for any IACTs facility, and in general, to all observatories with small field of view and limited duty cycle.

1. Introduction

Transient and variable emission has been observed from gamma-ray sources such as binary systems, active galactic nuclei and gamma-ray bursts. Variability studies shed light on physical processes responsible for the acceleration of charged particles and the photon emission in these objects. The determination of the characteristic physical time scales for particle acceleration and gamma-ray emission mechanisms, and their dependence on the relativistic beaming, allow us to gain an understanding of the origin of flares, and the size, structure, and location of the emission region.

The majority of variable gamma-ray sources detected at very-high-energy (VHE, from ~50 GeV to hundreds of TeV) are active galactic nuclei (AGN), powered by supermassive black holes accreting matter at the center of some galaxies. Most of the gamma-ray bright AGN are blazars, a subclass of AGN characterized by the presence of two collimated outflows of relativistic plasma (jets), streaming away from the central black hole along the line of sight, so that one jet is pointed towards the Earth [1]. Relativistic beaming of the emission of the jet enhances the luminosity of the source and shifts it to higher energies, making these sources bright VHE emitters; in fact, blazars account for ~1/3 of all the sources currently detected at these energies. Blazar emission spans through the entire electromagnetic spectrum and it is characterized by a strong temporal variability, observed on time scales ranging from years down to minutes.

The observation of variable emission patterns is challenging with IACTs, due to their small field of view and the fact that observations are limited to dark nights and good weather periods. For these reasons, observing strategies for IACTs must be carefully optimized in order to achieve their goal in as little time as possible. The common approach to observation planning makes use of the sensitivity to describe the performance of the instrument and compare it to the mean or low-state flux of the sources. This approach is not optimized to plan observations of strongly variable sources as it does not explicitly take into account the variability. In this work, variability is taken into account by the simulation of light curves similar to those measured for AGN. Various types of variability properties are considered. Different observing strategies are modeled and, for each one, the probability of detecting the sources is computed. This probability provides a measure of the performance of the observing strategy and is used to quantitatively compare different strategies. Two questions that are relevant

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* Corresponding author. Tel.: +49 1796507464.
E-mail addresses: matteo.giomi@desy.de (M. Giomi), lucie.gerard@desy.de (L. Gerard), gernot.maier@desy.de (G. Maier).

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in the context of observation planning are addressed: what is the fastest way to detect a weak, variable source with given variability characteristics, and which observing strategies are more suited to conduct variability-unbiased, blind-sky surveys.

Our work is applied here to optimize AGN observations with the Cherenkov Telescope Array (CTA), a future VHE gamma-ray observatory [2]. CTA will consist of 80–100 of telescopes of three different sizes, resulting in a ten times better sensitivity than any of the current IACT arrays and a wide, four-orders-of-magnitude, energy range. The observation of AGN will be one of the major goals for CTA, and simulations show that CTA will detect a large number ($\sim 10^3$) of these objects [3].

This paper is structured as follows: Section 2 presents the simulation of AGN variability. In Section 3, the model of the observing strategies is illustrated. Section 4 describes the method used to compute the performance of the observing strategies for a given set of variability properties. Finally, in Section 5 the optimal strategies to observe known sources and to conduct a blind-sky survey are identified.

2. Simulation of VHE AGN variability

The variability of a source is usually presented through its light curve, showing the flux in a given energy band as a function of time. VHE AGN light curves appear aperiodic. Flux variations down to the timescale of minutes have been observed for the brightest sources such as Mkn 421 [4], PKS 2155–304 [5], and Mkn 501 [6].

As of today, little information is available on the temporal properties of VHE AGN light curves. To attempt a description of the variability characteristics of the whole class of AGN, data collected at other wavelengths have to be considered. In particular we will refer to results from the *Fermi* Large Area Telescope (LAT) [7], observing the sky in the high-energy (HE, from tens of MeV to hundreds of GeV) band. By doing this we assume that variability properties observed in the HE band are representative of those in VHE. This working assumption might be supported since similar physical phenomena could be responsible for the emission in these two adjacent energy bands. However, it is worth stressing that the light curves we simulate are meant only to give a good representation of the available data; no attempt is made here to a detailed model of VHE AGN variability.

Fourier analysis is one of the most common and powerful tools used to characterize time series. Referring to its properties in the frequency domain, AGN variability is often described as power-law noise, i.e. the Power Spectral Density (PSD) of AGN light curves is well reproduced by a power-law function of the frequency ν, $P(\nu) \propto \nu^{-\beta}$, over a wide range of frequencies. Fourier spectral analysis has been performed on a sample of 156 BL Lacs and 56 Flat Spectrum Radio Quasars (FSRQs) in the second *Fermi* LAT AGN catalog (2LAC) [8]. In this case monthly binned light curves of the integral flux above 100 MeV are used, finding $\beta \sim 1.15 \pm 0.1$ for both source classes in the frequency range $[0.033, 0.5]\,\mathrm{month}^{-1}$. Similar analysis performed on a smaller sample of bright sources (22 FSRQs and 6 BL Lacs) for which three- and four-days binned light curves could be produced, lead to values of β of 1.7 and 1.5 for BL Lacs and FSRQs, respectively [9]. In the VHE energy domain the only case in which Fourier analysis of the light curve has been performed is the PKS 2155–304 2006 flare observed by H.E.S.S. The PSD for the 1 min binned light curve is compatible at 90% confidence level with a power law of index $\beta = 2$ in the frequency range $\sim [10^{-4}, 10^{-3}]$ Hz [5].

Another important feature of AGN light curves is a linear relation between the root mean square (RMS) amplitude and the mean flux of groups of contiguous bins of the light curve. This proportionality implies that fluctuations around the mean value, i.e. variability, are enhanced when the flux is higher. This has been observed in X-ray for many AGN and other accreting objects, like binary systems [10,11]. At VHE such behavior has been detected in the well studied PKS 2155–304 [12] and Mkn 421 [13]. As observed by Uttley and McHardy [14], and Biteau and Giebels [15], this RMS-flux proportionality represents a strong constraint on the models that must be used to reproduce AGN light curves. In particular, these authors have demonstrated that only models in which the simulated flux is obtained as the exponential of an underlying stochastic process are able to produce such a relation.

PSD properties and the RMS-flux relation define the variability profile of the light curves; the variance of the light curve sets the scale of the fluctuations. This quantity is more commonly expressed through the use of the fractional RMS amplitude F_{rms}[1]. Fractional RMS amplitudes ranging from 20% to 60% have been observed in the VHE light curve above 200 GeV of PKS 2155–304 [12]. Values of F_{rms} for most of the *Fermi* 2LAC sources are found to vary between 20% and 80% [8].

We simulate AGN-like light curves of the flux above 100 GeV, the typical energy threshold for VHE observatories. To produce time series exhibiting a power-law PSD and a linear RMS-flux relation, we follow the method proposed by Uttley and McHardy [14]. The light curve $\phi(t_i)$ is obtained through an exponential transformation of a linear, aperiodic time series with zero mean, $x(t_i)$:

$$\phi(t_i) = \exp[x(t_i)] \tag{1}$$

The Timmer and König algorithm [16] is used to produce the input time series $x(t_i)$. This algorithm produces linear time series with a power-law PSD of arbitrary slope. It must be noted that, as a consequence of the exponential transformation, the PSD of the resulting light curve $\phi(t_i)$ is different from that of the input time series $x(t_i)$. However, for the broad continuous PSD observed in AGN, this distorting effect is relatively small and can be neglected [14].

The exponential transformation of Eq. (1) enhances points above the mean while reducing points below the mean. As a consequence, when the variance of the Timmer and König time series $x(t_i)$ increases, flares in the light curve $\phi(t_i)$ becomes more prominent compared to the dips. The aspect of the resulting light curves $\phi(t_i)$ is thus influenced by the variance of the input time series $x(t_i)$, a parameter that is inherent to the light curve simulation algorithm but has no clear physical interpretation[2]. In this work this parameter is fixed for all the light curves: the Timmer and König series are normalized to $F_{\mathrm{rms}} = 50\%$ before taking the exponential transformation. Different normalization for the Timmer and König series have been tested and shown negligible impact on the conclusion of this work.

The choice of the frequency, i.e. the spacing between two contiguous points, and length, of the simulated light curves defines the range of Fourier frequencies that contributes to the signal. These parameters are chosen in such a way as to include contributions from all the frequency components that are currently probed by HE and VHE observations. The lowest frequency considered is $0.033\ \mathrm{month}^{-1}$, probed by *Fermi*-LAT for sources in the second LAT

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[1] $F_{\mathrm{rms}} = \sqrt{\sigma_\phi^2}/\langle\phi\rangle$, where $\langle\phi\rangle$ and σ_ϕ^2 are respectively the mean flux and variance of the light curve. This quantity expresses, independently from the source strength, the amount of variability in the light curve. When dealing with real data, the variance σ_ϕ^2 is more conveniently replaced by the excess variance [10].

[2] A possible workaround to this problem would be to assume a log-normal distribution for VHE AGN fluxes. Under this assumption, the statistical properties of the light curves can be related to the mean and variance of the input series $x(t_i)$, eliminating the need of this additional parameter. However, as of today, log-normal distributions of AGN fluxes have not been observed in VHE, if the entire light curve of the source is considered (see, for example, the bi-modal distribution of PKS 2155–304 flux over the 2005–2007 period as observed by H.E.S.S. [12]). Although log-normality at the highest energies is not ruled out, due to the generally poor sampling flux states of the sources, biased towards the observation of flares, we still prefer not to use this additional hypothesis.