High-speed imaging and its applications: Beating down the scintillation noise

Application Note

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Introduction

The photometric accuracy of the time series produced by space-based telescopes proved to be 2 to 3 orders of magnitude than that of ground-based observations. The profound reason for this discrepancy is the existence of the Earth's atmosphere and more specifically the "twinkle" or scintillation of stars.

The stars are twinkling due to wavefront curvature of the upper atmosphere. As a result, the light of any source that arrives in any photon collecting device, presents fluctuations in millisecond intervals. According to Reiger (1963) ~ 70% of the amplitude of the intensity fluctuations originate to perturbations in the incoming wavefront, at the altitude of 7 to 15 km. The impact of those fluctuations in the time series is the introduction of correlated (red) noise, in addition to the present photon (Gaussian) noise of the light curve.

Until present, a way to "fight" scintillation is the collection of a large number of photons, using very large telescopes (e.g. GTC, Keck, SALT, LBT, VLT), in time intervals far from the millisecond regime. Nevertheless and despite the obvious advantages, such massive structures are very expensive to build and maintain. In addition, the wide spectrum of applications that those telescope offer increases the demand for observational time. As a result the usage of such instruments for general studies such as surveys is usually not possible.

But is there another way to beat scintillation? The first step in order answer this question was made with a series of papers, by D. Dravins and colleagues (Dravins et al. (1997a), Dravins et al. (1997b) and Dravins et al. (1998)). In their work they attempt to describe the statistical characteristics of scintillation, using a variety of telescopes equipped with photomultipliers and they conclude that the intensity of autocorrelation is aperture-dependent for small apertures (~ 5 cm) and the delay of its maximum value varies between 1 ms and 10 ms. Also they noticed that the frequency of the scintillation fluctuations becomes smaller for longer wavelengths.

While photomultipliers are very good for scintillation studies, they suffer from a great disadvantage; their spatial resolution. Due to their construction, the photomultipliers are unable to spatially resolve the collected photons (i.e. they cannot create 2D images). Consequently, the observation of more than one source simultaneously through the same optical instrument is impossible. As a result, cross correlation studies of the scintillation fluctuations of different objects, suffer from additional systematic errors due to the usage of different telescope-photomultiplier couples for each source.

Due to the advance of the silicon charge-coupled devices (CCD), which can store photons in pixel arrays and not in only one pixel, the photomultipliers were put aside. Yet, this property of the CCDs makes them inappropriate of scintillation studies, due to the time that it is needed for the read out (the process of the digitization of the stored electrons). Thus, the scintillation studies were stalled.

Hence, the second step towards beating scintillation noise was made, indirectly, by Qiu et al. (2013), with the introduction of complementary metal-oxide semiconductor (CMOS) devices for scientific astronomical use. In a CMOS chip every row of pixels has its own analog-to-digital converter. This allows each row to perform the readout procedure, while the other rows are still exposing (rolling shutter mode). Due to that function a CMOS camera has readout times to sub-millisecond regime.

Equipment

The main idea behind the assembly of a fast imaging telescope as shown in figure 1 is the study of scintillation effects in the light curves of more than one star, simultaneously. Consequently the equipment was configured in favor of this idea.

The cameras used for our experiments are the sCMOS cameras Neo-5.5-CL3 and Zyla-4.2-CL10 from Andor Technology. Due to the technical advantages of the sCMOS chips, in comparison to regular CCD chips, these cameras can reach frame rates up to 100 fps in full frame operation. In addition the size of their chips, 2560 x 2160 pixels and 2048 x 2048 pixels, respectively, allows for wide field imaging, if combined with the proper optics and telescope.

The cameras are connected to a Linux PC and operated using the Andor's Software Developer Kit (SDK).

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Fig. 1: Set-up with C14, hyperstar and Neo-5.5 sCMOS camera at Hamburg Observatory.

Results

The results of the first observations are very promising: 1) We are able to measure the autocorrelation functions of multiple stars simultaneously, and 2) we manage to detect faint stellar signals, e.g. the pulsations of the delta-Scuti variable star ε-Cep.

The autocorrelation and autocovariance functions of the light curves of all our targets, agree with the results of Dravins et al. 1997a, and is presented in Fig. 2.

In addition, the measurement of the light curve statistics for multiple stars, using the same instrument, allows us to distinguish more easily the systematic trends and thus to compare more efficiently the effects of scintillation noise on light curves of different targets in the same field of view (FOV). The impact of scintillation in the precision of the light curves is very large, i.e., without the effects of scintillation, the transit of an Earth-like planet like 55 Cnc e would be visible. Systematic, high speed observations of multiple targets might allow us to eliminate the scintillation effects using differential photometry and more sophisticated data analysis, e.g. the application of a high pass frequency filter on high speed light curves.

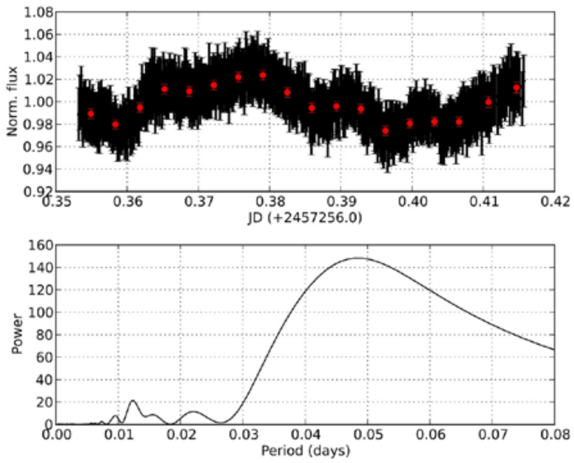

Figure 3: Top: The light curve of eps-Cep variable star. The black points are integrations of 790 exposures (10 sec) while the red points are integrations of 23700 exposures (5 mins). Bottom: The result of the Lomb Scargle periodogram over the light curve. The leading period is 0.048 days.

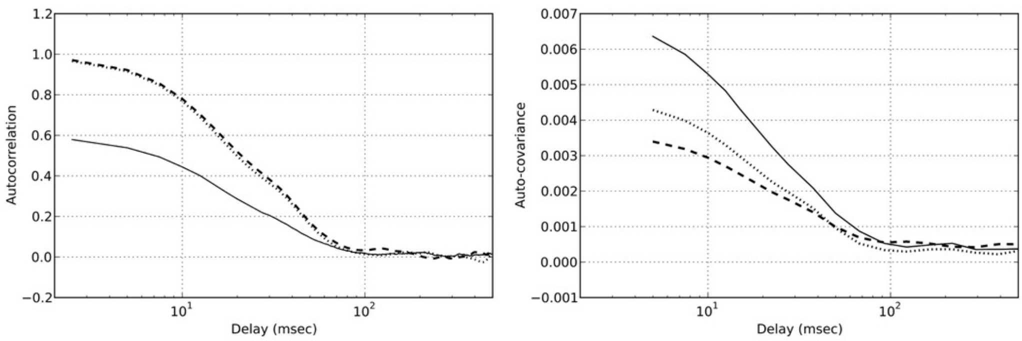

Figure 2: The autocorrelation (left) and auto-covariance (right) functions of the three stars. The results are in agreement with the results of Dravins et al. (1997a). The autocorrelation function of the fainter star has lower max-value, probably due to the increased noise in its light curve.

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In Fig. 3 we show the light curve of the delta scuti star ε-Cep. The detection of the pulsations of ε-Cep, using differential photometry, demonstrates the power of our fast imager. Its ability to reach precision levels lower than 0.5% (comparable to observations made by telescopes with much larger diameter, e.g. Mislis & Schmitt 2009), renders it ideal for follow up observations on bright variable stars and large exoplanets.

References

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