TEMPORAL PROPERTIES OF THE BRIGHTEST SPECKLE

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RESUMEN

Se presentan resultados experimentales sobre las propiedades temporales de la mota (*speckle*) más brillante. Los datos muestran que el tiempo de vida de la mota más brillante, definido como el tiempo de correlación a la altura media de la función de correlación temporal, es de aproximadamente 20 ms. El tiempo de vida más corto que observamos fue de 7 ms, y el más largo, de 70 ms.

La comparación de los resultados obtenidos en tres filtros nos permite concluir que el tiempo de vida de la mota más brillante disminuye al disminuir la longitud de onda. Comparamos el tiempo de vida de la mota más brillante con el tiempo de correlación del centroide de la imagen. El resultado es que el tiempo de correlación del centroide de la imagen es aproximadamente 10 veces mayor que el tiempo de vida de la mota más brillante.

ABSTRACT

The experimental results related to the temporal properties of the brightest speckle are presented. The analysis of the data shows that the lifetime of the brightest speckle, defined as a correlation time at the one-half height of the temporal correlation function, is about 20 ms. The shortest lifetime which we observed is about 7 ms while the longest is about 70 ms.

The comparison of the results obtained in three filters allows us to conclude that the lifetime of the brightest speckle decreases with decreasing wavelength. Also a comparison of the lifetime of the brightest speckle to the correlation time of the image centroid is performed. The comparison shows that the correlation time of the image centroid is approximately 10 times longer than the lifetime of the brightest speckle.

1. INTRODUCTION

The brightest speckle is an interesting phenomenon which appears in turbulence-distorted short-exposure astronomical images. Basing on the concept of the brightest speckle Bates & Cady (1980) suggested the shift-and-add (SAA) method used for the reconstruction *a posteriori* of high-resolution astronomical images from the sets of short-exposure images. The SAA method prescribes to find the brightest point (brightest speckle) in each image, to shift the image in such a way that this point is moved to the image center, and then to sum all the shifted images together. The resulting SAA-reconstructed image contains a telescope diffraction-limited image sitting on top of a seeing-limited pedestal.

The simplicity of this method makes it very suitable for the determination of the photometric and astrometric properties of close binary stars (Aspin et al. 1997; Pirzkal, Spillar, & Dyck 1997). This technique is also successfully used to obtain diffraction-limited images of red supergiants (Christou, Hebden, & Hege 1988), of Seyfert galaxies (Tomono et al. 2001) and of the solar granulation (Baba et al. 1999). Also the SAA approach can be applied not only for the *a posteriori* data reduction, but also for the real-time adaptive correction. In comparison to an advanced adaptive system which assumes a complicated wavefront sensor and a flexible mirror, the SAA method is very simple and inexpensive because it just consists of two main elements: a CCD cam-
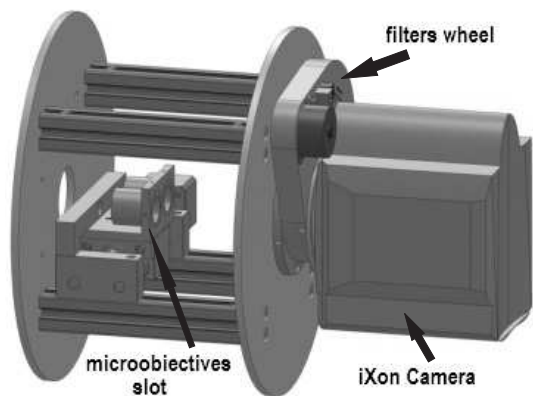
Fig. 1. Experimental Equipment.

era and a tip-tilt corrector. Furthermore, for some applications the SAA method can be more efficient than adaptive optics (AO) systems (Christou 1991). Also, the non-isoplanarity affects less the SAA technique (Bagnuolo 1984) than the AO one (Orlov et al. 2003).

Taking into account the above considerations it is interesting to know how fast the position of the brightest speckle is changing with time, or, in other words, how long the lifetime of the brightest speckle is. In this paper we present the results of experimental investigations related to the temporal behavior of the brightest speckle. The study is performed with data obtained with a high-speed CCD camera at a 1-m telescope. To estimate quantitatively the lifetime of the brightest speckle we use a common approach based on the analysis of the corresponding temporal correlation functions. This approach allows us to characterize the temporal behavior of the brightest speckle by a single parameter, named the correlation time (in what follows, we use the term "lifetime" instead "correlation time") of the brightest speckle. Then, with this parameter on hand, we can easily compare the results obtained from a different observations or for different phenomena (for example, to compare the temporal behavior of the brightest speckle and the image centroid).

2. EXPERIMENTAL EQUIPMENT, OBSERVATIONS, AND DATA REDUCTION

The main parts of the equipment used for observations are shown in Figure 1.

The most important component of our experimental equipment is the iXon (DU–885K–CS0–#VP) EMCCD camera manufactured by Andor company. This camera has an 1002×1004 px CCD but allows to grab the images from a smaller area permitting high-speed data recording (cropped
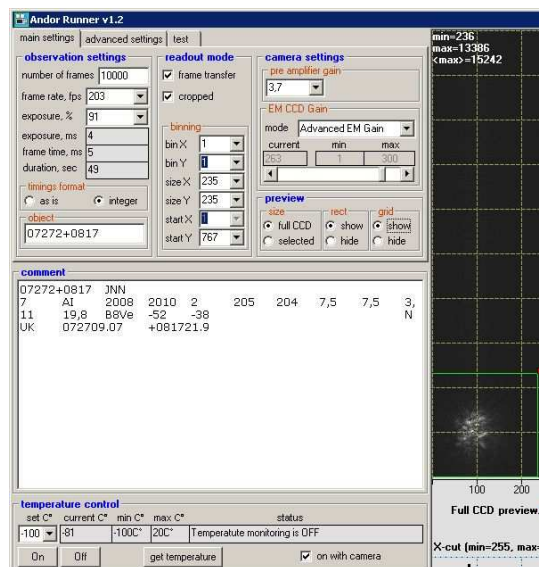

Fig. 2. AndorRunner: the program to control iXon CCD camera during observations.

mode). In our observations we recorded the images from a 235×235 px area using this mode. It was the smallest area inside which, under the given turbulence conditions, we were able to keep the whole turbulence-degraded star image during the frame recording. The CCD readout speed was chosen as the "fastest recommended" by the camera manufacturer. With such a setting the camera was able to provide the maximum frame rate equal to 200 frames per second (fps). The CCD matrix is of EM CCD type which provides a high light sensitivity. Also the camera has a cooler to maintain automatically the CCD temperature equal to -85C (the minimum temperature which the cooler was able to provide). During our experiments we used the 14-bit output mode (16384 discrete levels in the output signal). The pre amp gain was set equal to 3.7 while the EM CCD gain was chosen depending of the magnitude of the observed star in such a way that the maximum readout level was between 10000 and 14000.

Before entering into the CCD the light collected by the telescope passes thought the micro objective and the filter. The micro objective allows us to obtain a more detailed star image, which is important for our investigations. In the current investigations we chose the micro objective in such a way that the resulting scaling was 0.047 arcsec/px. This scaling, on the one hand, provides a sufficiently detailed image and, on the other, allows us to put the whole image inside a relatively small CCD area. Both the filters and the micro objectives are remotely-
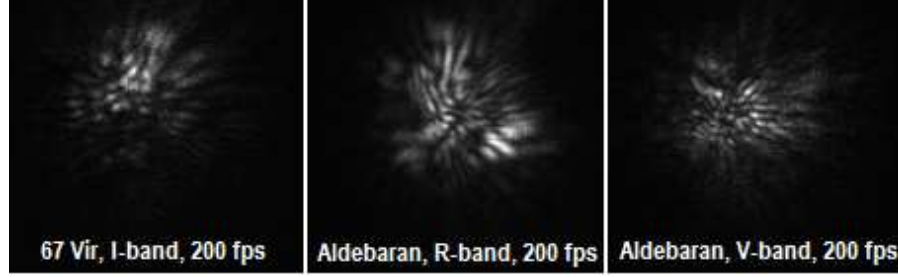
Fig. 3. Examples of recorded short-exposure images for three bands. Frame rate: 200 fps, exposure: 4 ms.
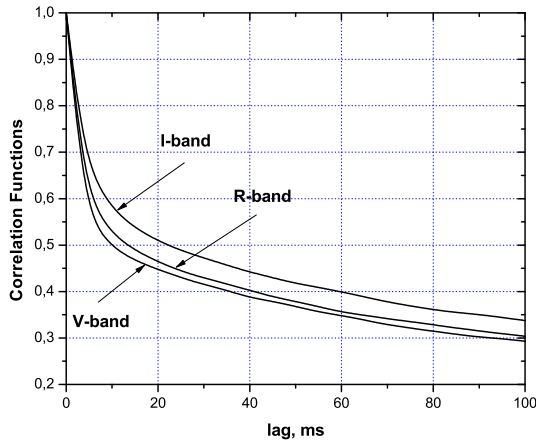

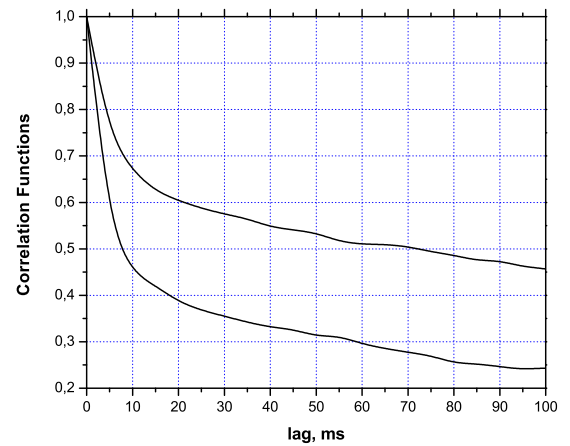Fig. 4. Temporal correlation functions of brightest speckle.

Fig. 5. Two limiting cases: longest and shortest lifetime of the brightest speckle for the I-band.

controlled, permitting their fast changing during the observations.

In order to simplify the camera usage in astronomical observations a program named AndorRunner was developed (Figure 2). AndorRunner is designed in such a way that it allows to control interactively all the settings and options of the camera during the observations. Also, it records all the camera parameters and user-defined comments in each data file, which simplifies the data reduction.

The observations were carried out during three nights in February, 2013 at the 1-m telescope located in Tonantzintla, Mexico. The seeing conditions were quite typical for this place (about 2 arcsec FWHM).

All the data were obtained in three filters (V, R, and I band). In total we got 36 sets of data (12 sets for each filter), each set with 10000 frames grabbed from a 235×235 CCD subarea with a speed of 200 frames per second (4 ms exposure time). All the stars used for the observations were chosen near to the zenith and bright enough to provide a high-speed recording with a small amount of noise. Some examples of the recorded images are shown in Figure 3.

The data reduction consists of two steps. As a first step the coordinates of the brightest speckle and the image centroid are calculated for each frame and saved in a separate file. The coordinates of the brightest speckle are defined as the coordinates of a pixel with the maximum intensity. As a second step the statistical properties of the quantities of interest are calculated. The results of the data reduction are presented in the next section.

3. RESULTS

Figure 4 shows the temporal correlation functions of the brightest speckle for three bands (I, R, and V). Each of the three graphs is obtained by averaging over 12 sets of observations. To simplify the future analysis of data we define the lifetime of the brightest speckle as the correlation time at the one-half height of the temporal correlation function. Analysing the results presented in Figure 4 one can see that the averaged lifetime of the brightest speckle is about 20 ms (for the I-band). Also, it is clearly seen how the lifetime of the brightest speckle depends on the bandpass: it increases with increasing of wavelength.
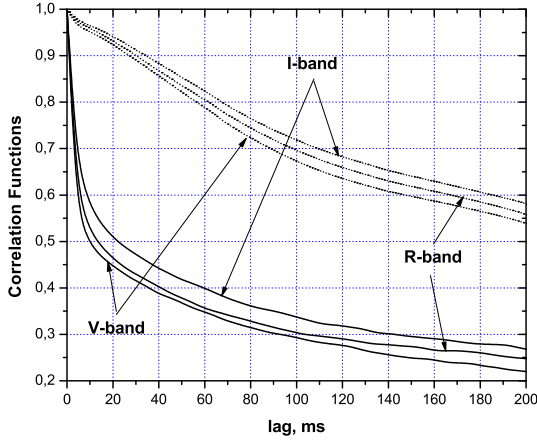
Fig. 6. Temporal correlation functions of the brightest speckle (solid lines) and the image centroid (doted lines).

Figure 5 presents the two limiting cases which we found in our observational data: the shortest and the longest lifetime of the brightest speckle (for the *I*-band). Looking at the graphs one can conclude that the shortest lifetime is about 7 ms while the longest one is about 70 ms.

Figure 6 compares the temporal correlation functions of the brightest speckle to these of the image centroid. Analysing the graphs in Figure 6 one can conclude that the brightest speckle is moving much faster (approximately 10 times faster) than the image centroid. Also one can see the wavelength dependency: the shorter the wavelength the faster both the brightest speckle and the image centroid are moving.

4. CONCLUSIONS

The results of our experimental investigations related to the temporal properties of the brightest speckle have been presented. The analysis of the data obtained has shown the following salient features of the temporal behavior of the brightest speckle.

1. On average, the lifetime of the brightest speckle observed in our data is about 20 ms (for the *I*-band).

2. The shortest lifetime which we observed was about 7 ms while the longest was about 70 ms (both quantities are given for the *I*-band).

3. The lifetime of the brightest speckle increases with increasing wavelength.

4. The brightest speckle is moving much faster (approximately 10 times faster) than the image centroid.

5. Both the brightest speckle and the image centroid show the same behavior with changing wavelength: the shorter the wavelength the faster both quantities are moving.

The experimental results obtained can be useful for high-resolution astronomy and adaptive astronomical optics. In particular, one of the more promising areas where these results can be applied is the development of shift-and-add astronomical adaptive systems. The main advantage of these systems is that, in comparison with conventional ones, they are quite simple and inexpensive. Using the results presented here, one can estimate the correction speed needed for such type of adaptive systems and evaluate how this speed depends on the wavelength. The present paper is the first one in a series related to experimental investigations of turbulence-degraded astronomical images. This paper is mainly devoted to the analysis of the brightest speckle as a physical phenomenon, while in the next publication we are going to present results of more practical interest. These results will be based on experimental data to be obtained at two observatories with very different turbulence conditions, and will show how the efficiency of shift-and-add adaptive correction depends on the correction speed.

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