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Magnitude Differences measurements for speckle Interferometric binaries

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Abstract: **A method of magnitude differences measurements for speckle interferometric binary stars is presented. The method is based on standard power spectrum analysis of speckle series without correction speckle interferometric transfer function. Both accuracy and sources of systematical errors are analyzed. Photometrical accuracy range within between $0.^m02$ and $0.^m1$, depending on the seeing, separation and brightness of the components.**

Introduction:

Binary stars study is the most useful direct way to connect stellar theoretical models with the actual observational results.

At present speckle interferometry become the main method for accurate astrometry of binary and multiple stars (Hartkopf et al. 2001). Unfortunately, high-accuracy photometry of the individual components using this method still remains unsolvable problem (Worley et al. 2001). Among more than 70000 measurements of magnitude differences for binaries components only 676 ones were made with different interferometric techniques (Mason & Wycoff 2003). Accuracy of such estimations ranges within $0.^m1$ and $0.^m5$, where it is worse than $0.^m2$ for most of them. Furthermore, other techniques were and still not able to overcome the problem, especially for separations smaller than $0.''3$. In this poster we describe a new method for determining the magnitude differences, bases on standard power spectrum analysis of speckle series.

Measurements of magnitude differences:

Determination of magnitude differences Δm by interferometric methods leads to measurements of either peak amplitude ratio of the object autocorrelation function, or fringes contrast of the mean object power spectrum (visibility function). The mean power spectrum of speckle interferometric frames can be expressed as:

$$\langle|I(\nu)|^2\rangle = |O(\nu)|^2 \langle|S(\nu)|^2\rangle + N(\nu) \quad \text{.............................(1)}$$

where ν is the spatial frequency vector, $O(\nu)$ are Fourier transforms of the object intensity distribution, $\langle|S(\nu)|^2\rangle$ is the speckle interferometric transfer function (STF), and $N(\nu)$ represents the mean power spectrum of the noise events. Photon noise $N_p(\nu) = C_p n_p(\nu)$ (Goodman & Belsher 1976) and detector noise $N_d(\nu)$ predominantly contribute to the function $N(\nu) = N_p(\nu) + N_d(\nu)$. For modern photon counting devices the effect of the detector noise is negligible in comparison with the photon bias term and Δm measurements are limited mainly by the effect of the photon bias on the power spectrum estimations.

The normalized photon bias $n_p(\nu)$ depends on the shape of photon events. It can be easily determined as a normalized power spectrum of the "flat field" frames. Photon bias amplitude C_p can be obtained from the power spectrum beyond the telescope cut-off frequency, where the signal is equal to zero.

The main problems of deriving Δm are:

1- The required accuracy of the approximation for the photon bias amplitude is a fraction of a percent, whereas the usual accuracy is about several percents.

2- The function $n_p(\nu)$, which derived from the "flat field" frames do not vary appreciably in the power spectrum of speckle interferometric frames, due to some registration nonlinearity for example.

3- The deconvolution is known to be a non-trivial procedure.

Binary stars, Circular symmetric STF:

The photon bias changes the contrast of the power spectrum fringes and affect Δm estimation. Let us assume, that the STF is circular symmetric. In this case, we may select the annular area near spatial frequency ν, which is such narrow, that the STF $\langle|S(\nu)|^2\rangle$ may be considered to be constant. If the value of the amplitude C_p is fixed, both astrometric and photometric solution can be obtained in the annular area by a least squares fitting with the model function

$$F_2(\nu) = \alpha + \beta\, Cos(2\pi\nu\rho) \quad \text{.............................(2)}$$

where α and β represent unknown constants, and ρ is also an unknown vector of the system separation. Weighted mean values of the positional parameters ρ and θ, derived from different annular areas, can be used in the successive Δm determination.

Let us determine a contrast function as

$$C(\alpha,\nu) = 2\alpha/\beta \quad \text{.............................(3)}$$

if the resolution of the detector exceeds the telescope resolution limit, then the photon bias term decreases very slowly in comparison with $|O(\nu)|^2$. So, dependence of fringe contrast (magnitude difference) on the annular area radius arises, when the amplitude C_p occurs to differ from its true value (Figure 1). To eliminate such dependence, we should select amplitude C_p under the condition $dC(\alpha,\beta)/d\nu = 0$. This condition must be true in the appropriate range of spatial frequencies, excluding both atmospheric seeing and noisy data influence. The derivative of $dC(\alpha,\beta)/d\nu$ forms a slope of the first order weighted least squares fitting for $C(\nu) = C_o + C_1\nu$ dependence. The weights of the measurements are selected according to the relative rms of the coefficient β.

Intensity ratio of the components A/B can be obtained, using

$$(A^2+B^2)/AB = A/B + B/A = C_o, \quad \text{.........................(4)}$$

when C_1 is equal to 0, and

$$\Delta m = m_A - m_B = -2.5 \log(A/B), \quad \text{.........................(5)}$$

respectively. The error of the magnitude difference $\sigma_{\Delta m}$ can be obtained from σC_o in a conventional way.

Binary stars, Noncircular STF:

It is worthy to note that we did not use circular symmetry of the STF, but only demanded it to be constant within areas selected for fitting. That is why, the above formalism is applicable for any STF, Replacing annular areas with areas, where the STF is constant.

Elliptical transfer functions, which are constant within annular areas bounded by ellipces, appear to be rather a good approximation for most of the cases.

Note that ellipticity causes some oscillations in the contrast function, obtained from the circular annular areas (Figure 2).

Parameters of areas where the STF is constant (CTFA, constant transfer function

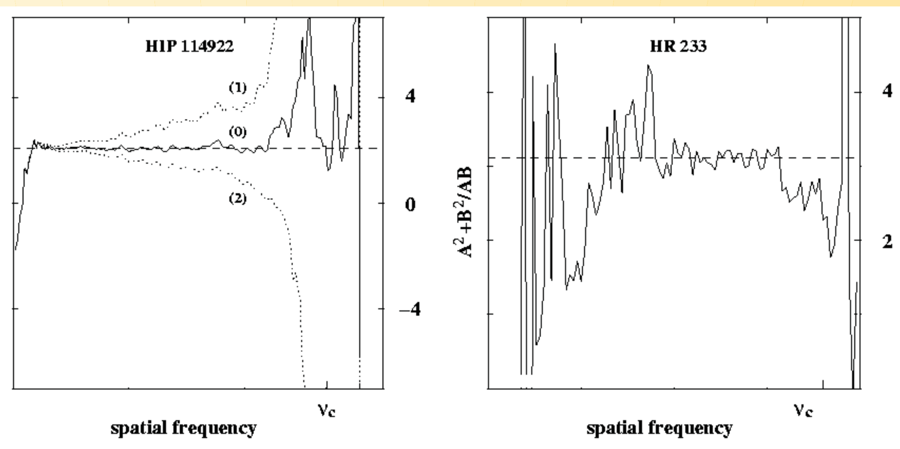

Fig. 1: Constant functions versus spatial frequency ν for binaries HIP114922 ($\rho=0.''107$, $V=11.^m3$, $\Delta m=0.^m16 \pm 0.^m09$), photon bias amplitudes $C_p^1 < C_p^0 < C_p^2$ and HR233 ($\rho=0.''016$, $V=5.^m4$, $\Delta m=1.^m08 \pm 0.^m08$). The telescope cut-off limit ν_c is shown.

area), and vector of the system separation can be estimated simultaneously by an iteration process. A condition to determine such areas is that the correlation coefficient between the power spectrum in this area and $Cos(2\pi\nu\rho_0)$

$$\kappa = [|O(\nu)|^2 \langle|S(\nu)|^2\rangle\, Cos(2\pi\nu\rho_0)]/\sigma_p\sigma_m \quad \text{.........................(6)}$$

where ρ_0, which is a previous estimation of ρ, must reach the maximum. The quantities σ_p and σ_m are rms errors of power spectrum and $Cos(2\pi\nu\rho_0)$ in the area, respectively. Such approach provides quite reliable results until ρ and Δm values are uncorrelated

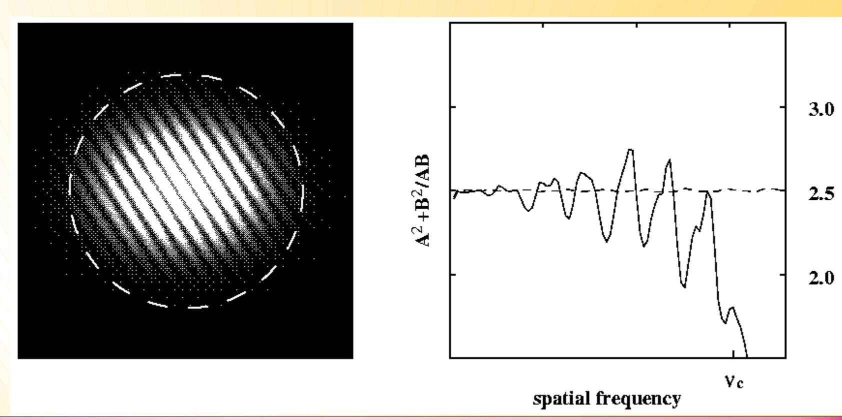

Fig. 2: Noncircular OTF influence for contrast function measurements. A power spectrum (left) and the contrast function of a binary star ($\Delta m=0.^m753$) model (right) are presented. Contrast function was determined assuming both cilcular (dashed) and elliptical (line) STF. The cut-off limit ν_c is shown (dashed circle).

($\rho > 2\lambda/D$, D is telescope diameter, λ is wave length). Otherwise, correlation between areas parameters and ρ arises, and the algorithm becomes inapplicable. A reference star is needed to determine CTFA in this case. Either a single star or rather a wide binary can be used as a reference one. The contrast function for the binary HR 233 is presented in Fig.1 as an example of this case.

Statistics and accuracy of Δm measurements:

We used the above method to measure multiple stars parameters during our speckle interferometric observations in 1998 and 1999 (Balega et al. 2002, 2003). The program of the stars lie within magnitudes between 2^m and 13^m, separations between $0.''016$ and $2''$ and magnitude differences between 0^m and $3.^m7$ (Figure 3, up).

As a result, 251 measurements for Δm have been made with $0.^m02$ to $0.^m15$ uncertainties, depending on system's brightness, Δm, separation (Figure 3, down) and atmospheric seeing. Accuracy distribution for the all stars are presented in Figure 4. Median value of the accuracy is about $0.^m06$. Initial consistency of the measurements have been tested by comparing Δm_{1998} and Δm_{1999}, obtained during observations on 1998 and 1999 (Figure 5, left).

The statistic analysis confirms a high self-consistency of our measurements and validity of the measurements precision with 47% and 60% importance level respectively.

Comparison with others measurements:

Reliability of the data was examined also by comparing of our results with the literature data. The results (Fig. 5) clearly show that a bias about 0.08 exists between the speckle interferometric and HIPPARCOS measurements. This is mainly due to the speckle interferometric limited field of view.

Let us split a frame into some areas, which are defined by Figure 6, and let us define window functions W_i as:

$W_i(r)=1$ inside the i-th area and $W_i(r)=0$ outside the i-th area.

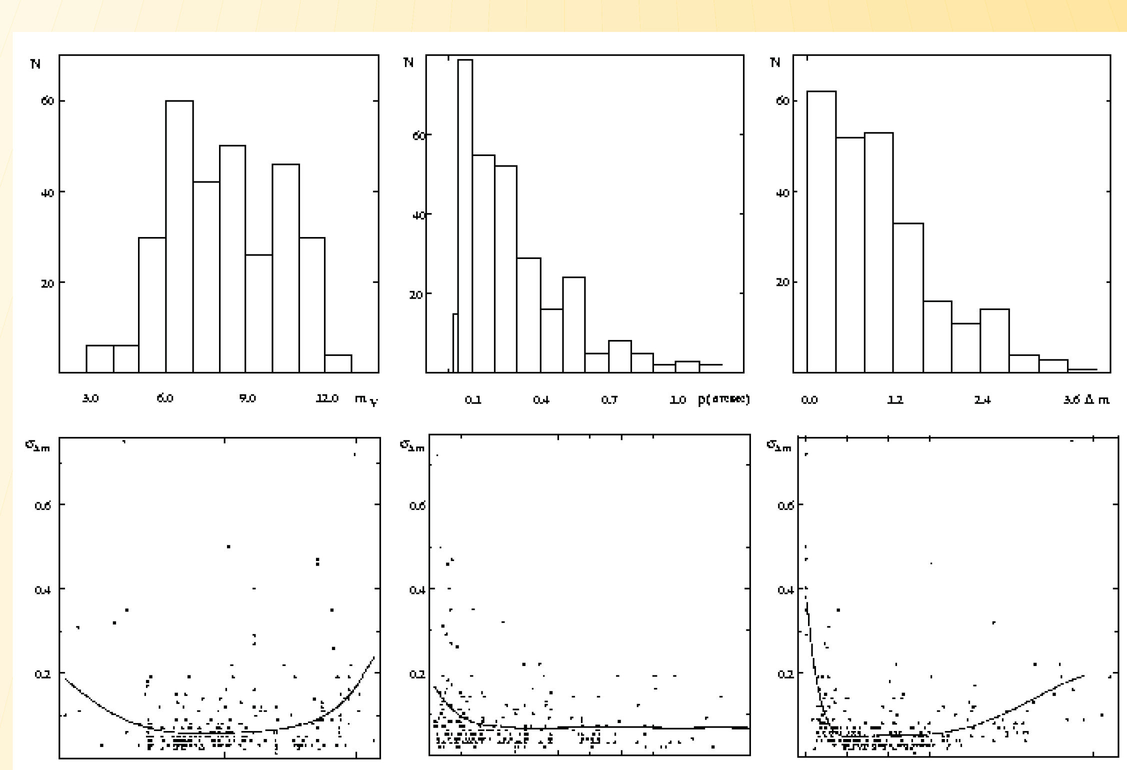

Fig. 3: Δm and $\sigma_{\Delta m}$ distributions during observations on 1998, 1999 (Balega et al. 2002, 2003).

Let $S_W(\nu)$ and $S_B(\nu)$ be the power spectra of the speckle series $\{I(r)W_W(r)\}$ and $\{I(r)W_B(r)\}$ respectively. It is easy to understand that the weighte of sum $S(\nu) = \omega_1 S_W(\nu) + \omega_2[S_W(\nu) - S_B(\nu)]$ keeps fringes contrast (autocorrelation peaks ratio) unbiased when $\omega_1 = N_A A^2 + N_B B^2$, $\omega_2 = N'_A A^2 + N'_B B^2$, A and B are middle intensities of the primary and secondary speckles, N_A and N_B are numbers of the primary and secondary speckles in the BA contributing to the secondary autocorrelation peaks, and N'_A and N'_B are numbers of the speckles in the BA not contributing to the secondary peaks. Ratio of weights ω_1 and ω_2 may be roughly estimated as:

$$\omega_1/\omega_2 = \int_{I}\langle I(r)\rangle dr \,/\, \int_{I}\langle I(r)\rangle dr$$

where $\langle I(r)\rangle$ is the average image, *I* and *II* are two areas near the frame's boundary separated by vector ρ (Figure 6). Determined power spectra $S(\nu)$ such a way can be used to obtain unbiased Δm values.

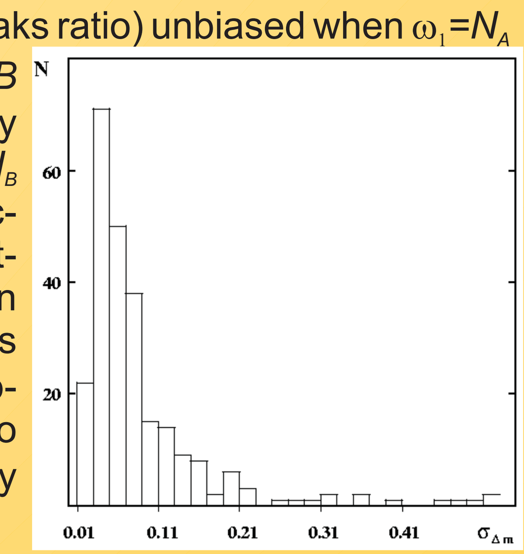

Fig. 4: $\sigma_{\Delta m}$ distribution during 1998, 1999 observations.

In Figure 5,b we present our Δm_{545}, which is corrected with described algorithm together with the literature data. Least square fitting of the relation between corrected Δm_{545} and HIPPARCOS Δm yields

$$\Delta m_H = -0.03[\pm 0.03] + 1.2[\pm 0.03]\, \Delta m^c_{545}$$

taking into account both our data and HIPPARCOS data errors as well as the difference between spectral bands, and supposing that consistency corrected and HIPPARCOS data are excellent.

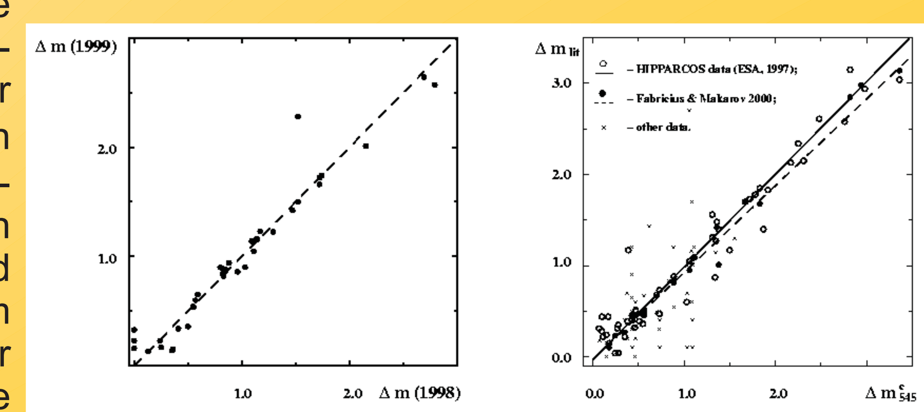

Fig. 5: Δm_{1998} versus Δm_{1999} (right), and Δm^c_{545} versus literature data (Δm_{lit}).

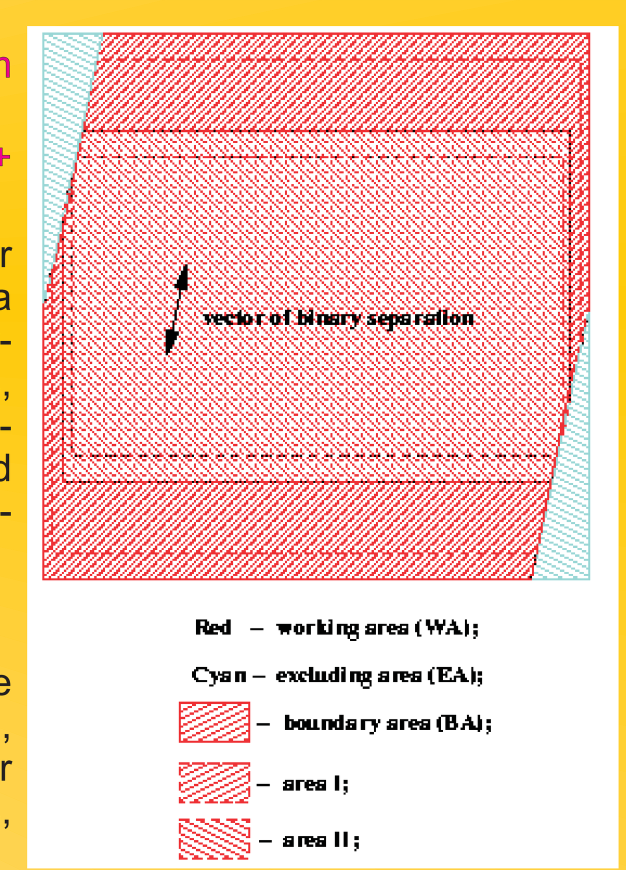

Fig. 6: Definitions of frame areas.

Summary:

A new method for magnitude differences measurements, based on a common order power spectrum estimations, was developed. The method provide accurate photon bias correction procedure, which is necessary to obtain precise parameters of speckle interferometric binaries and multiple stars brighter than 12^m.

Measurements errors lie between $0.^m02$ and $0.^m15$, depending on atmospherical seeing, brightness, separation and magnitude difference of the system. Mean value of magnitude difference errors, based on measurements by Balega et al. (2002) and Balega et al. (2003), was about $0.^m06$.

There is no need to correct the speckle interferometric transfer function by a deconvolution procedure with the method.

Examination of our data obtained during different observational sets and their comparison with Δm from the literature demonstrates the high self-consistancy and reliability of the method.

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