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Reduction of the binary stars Δm measurements, obtained with the speckle interferometer of BTA of SAO RAS, into the standard photometric system

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Abstract. For magnitude difference, measured with the speckle interferometer of the 6 m telescope of SAO RAS, corrections for transformation from interferometer's photometric system into standard Johnson-Causins VRI bands are calculated. The reduction accuracy is $0.01^m - 0.02^m$. To determine the correction one has to know the magnitude difference in the V band or in the interferometer filter close to it with $\lambda_{eff} = 545nm$ and the total color index of the system $(V-I)$. The systematic difference of the obtained Δm from it's real value is estimated by comparison with Hipparcos measurements.

Key words: methods: analytical – techniques: high angular resolution – techniques: photometric – stars: binaries

1. Introduction

The speckle interferometry is one of the extensively used techniques for the investigation of multiple stellar systems which are often inaccessible to studying by other methods. Apart from astrometrical information (positional parameters ρ and θ), the speckle interferometry aids us to determine the components' magnitude difference Δm. In combination with the classical photometry of the entire system it makes it possible to compute individual magnitudes and colors of the components. Often it is the only way to determine their physical parameters, especially for close pairs with $\Delta m \geq 2^m ... 3^m$, when the contribution of the second component to the combined spectrum is negligible and separate photometry is impossible.

Thus, obtaining accurate values of Δm in standard photometric systems is one of the goals to be performed by the speckle interferometry of multiple stars.

The system of filters used in the speckle interferometer of the 6 m telescope of SAO RAS differs from the standard one. Since to produce a clear interference pattern, the photometric band should be as narrow as possible and the FWHM of the curves of throughput of the interferometer filters make a few hundred angstroms (Table 1). In the standard $UBVRI$ system the passbands are a few times wider, and correct usage of the estimated magnitude differences for determination of physical parameters is impeded.

In particular, the error of the effective temperature determination from the magnitude difference measured in the filter close to the V band with $\lambda_{eff} = 545nm$ is $\approx 120K$ (approximately one subclass) for dwarfs of class FO, which diminishes the accuracy of model calculations allowing to obtain the value of T_{eff} with an accuracy better than $100K$. When we use the values of Δm obtained with redder filters of the interferometer as the magnitude difference in the R, I bands, the error may amount to $300K$ $(2-3$ subclasses) and even more.

All this makes it necessary to perform transition to the standard system for the determination of physical parameters of the components.

In the present paper we have got the reduction coefficients which enables transformation from the magnitude difference Δm_{SI}, obtained with the BTA speckle interferometer, to the Δm_{JC} in the standard Jonhson–Causins system.

2. Passbands of the photometric systems

In Fig. 1 we present the normalized light transmission curves of the BTA speckle interferometer (Maksimov et al. 2003) and also standard V, R, I Jonhson–Causins passbands taken from (Pickles 1998). The light transmission curves for the BTA speckle interferometer are given with allowance made for the IT sensitivity and the mean atmospheric transparency (Allen 1977), that is, the curves are leaned upon the

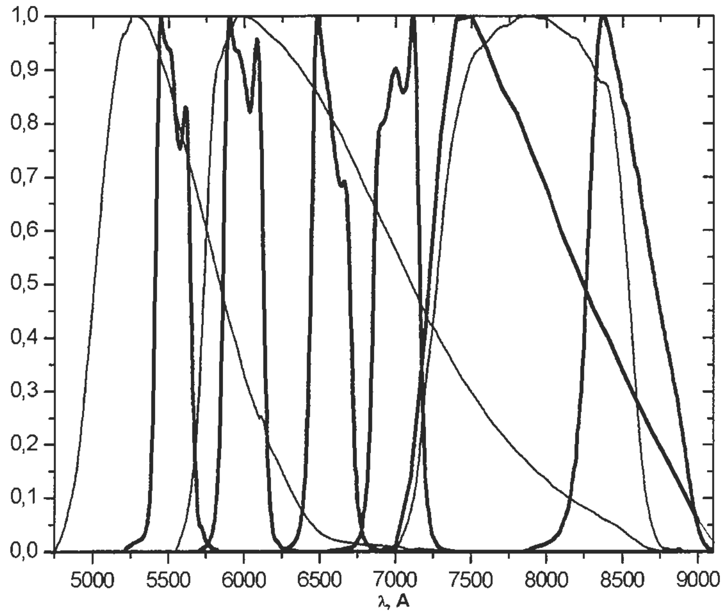

Figure 1: *Passbands V, R, I of Johnson-Causins system (drawn with thin lines) and light transmission curves of the speckle-interferometer of BTA SAO RAS (thick lines). All the curves are normalized to unity.*

Table 1: *Characteristics of filters of the BTA speckle interferometer used for photometry*

λ_{eff}, Å	FWHM, Å	Matched Johnson–Causins bands
5450	300	*V*
6000	260	*R*
6560	280	*R*
7000	320	*R*
8000	1030	*I*
8500	740	*I*

all variations of spectral flux density.

It can be seen from Fig. 1 that the filters used at BTA execute transformation to the V, R, I bands of the Jonhson–Causins system. Transition to the medium-band system of Stremgren is impossible because it's passbands are located in a more shortwave part of the spectrum and only reduction to the y band ($\lambda_{eff} = 5470$ Å) (Straizis 1977) of this system is possible.

The central wavelengths and the FWHM of the light transmission curves of the speckle interferometer and also the matched bands of the standard system are shown in Table 1 (Maximov el al. 2003).

3. Reduction to the standard system

3.1. Selection of standard spectra

Corrections for the obtained magnitude difference depend not only on photometric bands but also on the spectral class of the systems components. This is why for obtaining the corrections it was necessary to use standard spectra.

A comparison of the corrections defined for different luminosity classes has shown that they coincide within $0.01^m - 0.02^m$, and therefore the inaccuracy of the preliminary determination of the luminosity class of the components does not effect the accuracy of reduction.

Computations were conducted for systems consisting of normal stars of spectral classes from AO to $M5$ of luminosities III, IV and V.

As reference energy distributions the library of spectra (Pickles 1998) was used. There averaged distributions of energy are presented with a resolution of about 500. All spectra are normalized to unity at $\lambda = 5556$Å.

3.2. Calculation of reduction coefficients

For each of the standard energy distributions magnitudes in the filters used in the speckle-interferometer were computed by the formula

$$m_{i,j} = -2.5 \cdot lg \int_0^\infty F_i(\lambda) \cdot \phi_j(\lambda) \cdot d\lambda + const_j, \quad (1)$$

where $F_i(\lambda)$ is the energy distribution in the i-th standard spectrum, $\phi_j(\lambda)$ is the light transmission curve of the j-th filter. The constant was assumed to be equal to 0. For the sake of convenience the spectra were renormalized in accordance with the absolute magnitude M_V of a star of given spectral class taken from (Allen 1977; Cox 2000). The renormalization was performed for the area under the energy distribution curve was matched by luminosity of the given star, and the constant in formula (1) was the same for all the spectra when calculating the stellar magnitude in the given band. Then the constant itself has no effect on the computation of the corrections since subsequently only differences in stellar magnitudes are used. Further, the magnitude difference in each of the radio interferometer filters Δm_{SI_j} was calculated.

After this the correction was found as

$$\delta_{k,l,j,n} \equiv \Delta(\Delta m_{k,l})_{j,n} = \Delta m_{JC_{k,l,j}} - \Delta m_{SI_{k,l,n}}, \quad (2)$$

where $\Delta m_{JC_{k,l,j}}$ is the magnitude difference of the spectrophotometric standards k and l determined in the standard band j. $\Delta m_{SI_{k,l,n}}$ is the magnitude difference of the same standards in the filter n of the interferometer. Thus, the value $\delta_{k,l,j,n}$ is the correction of transformation from the filter n to the standard filter j for a system consisting of stars of classes k and l. The computations were made for all available standard spectra.

4. Observed characteristics of binary systems and determination of corrections

Note that the usage of corrections determined through the spectral types of the components is difficult in practice since we must ***already*** know the spectral class of the components for this.

At the same time, it is easy to transit from the terms of spectral types of the components to the terms of Δm_V and *color*, where Δm_V is the magnitude difference in the V band, *color* is any total color index of the system. In particular, we used the index $(V-I)$:

$$(V-I)_{syst} = (V-I)_{primary} - 2.5 \cdot lg(1+2.512^{-\Delta m_V}) + $$
$$+2.5 \cdot lg(1+2.512^{-\Delta m_I}). \quad (3)$$

The pairs $(\Delta m_V, color)$ can be obtained directly from observations. Here the uniqueness of the transition requires to know the luminosity class, which is estimated reliably enough from the spectrum of the system.

Thus, corrections were calculated in terms of matrices $(\Delta m_V, (V-I)_{syst})$ for Δm_V from 0.0^m till 4.0^m corresponding to the whole range of stellar magnitude differences accessible to the BTA speckle interferometer. Here $(V-I)_{syst}$ changes from 0.1^m to 2.8^m. $(V-I)_{syst} = 0.1^m$ corresponds to a system consisting of A-stars, $(V-I)_{syst} = 2.8^m$ to a system of components $M5$.

The corrections graphs for different filters are shown in Figs. 2–8. Figs. 2, 3, 4, 5, 6, 7 illustrate corrections in different filters for the system consisting of main sequence stars.

The family of the curves corresponds to different colors $(V-I)_{syst}$. Δm_V is laid of as abscissa, the correction value is plotted as the ordinate.

In Fig. 8 are exhibited the same curves as in Fig. 2, but the color of the system $(V-I)_{syst}$ is plotted as the abscissa, and the family of the curves corresponds to different values of Δm_V.

The coefficients of the polynomials for analytical approximation of the relationship $\delta(\Delta m_V, (V-I)_{syst})$ are given in the Appendix.

5. Determination of Δm_V and the accuracy of reduction

The components magnitude difference in the V band is not always known since this requires involvement of observational data obtained with other instruments, whose photometric bands does not always correspond to the standard system as well. But $\Delta m_{545/30}$ — the magnitude difference in the filter with $\lambda_{eff} = 545nm$ — is the value obtainable from our observations. On its basis, using the iteration method, one can find Δm_V.

From the relationships that we have derived (Fig. 2) it follows that the values of reduction corrections in transformation from the filter $545/30nm$ to the V band does not exceed $\pm 0.08^m$. The required accuracy of reduction is $\pm 0.01^m$ because the value of the intrinsic error of the magnitude difference determination in BTA speckle interferometric observations is no better than $0.02^m ... 0.05^m$ (Balega et al. 2002).

Assuming $\Delta m_V^1 = \Delta m_{545/30}$ as an initial approximation, we commit an error in magnitude difference determination in the V band $\epsilon_{\Delta m_V} \leq 0.08^m$. The error of the reduction correction δ (2) can be estimated from the inequality

$$\epsilon_\delta \leq (\epsilon_{\Delta m_V})_{max} \cdot \frac{\partial \delta}{\partial(\Delta m_V)}. \quad (4)$$

It can be seen from Fig. 2 that the value of $|\frac{\partial \delta}{\partial(\Delta m_V)}| \leq 0.1$ and is, as a rule, a value an order of magnitude smaller.

Then ϵ_δ in the V band will not exceed $0.08 \cdot 0.1 = 0.008^m$, which satisfies the required accuracy.

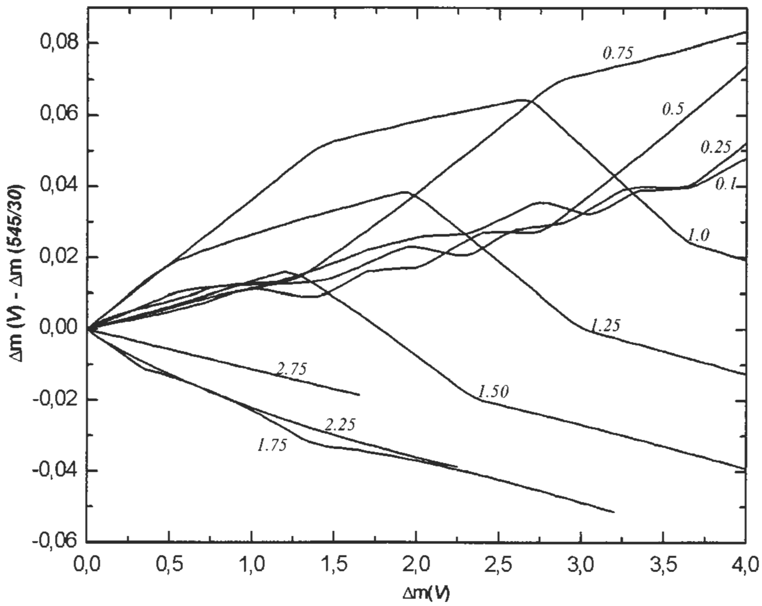

Figure 2: *Corrections of transfer from the filter* 545/30 *to the* V *band for systems consisting of stars of* V *luminosity class, depending on* Δm_V*. The family of curves corresponds to different* $(V - I)_{syst}$*, the values of which are written at the corresponding curves.*

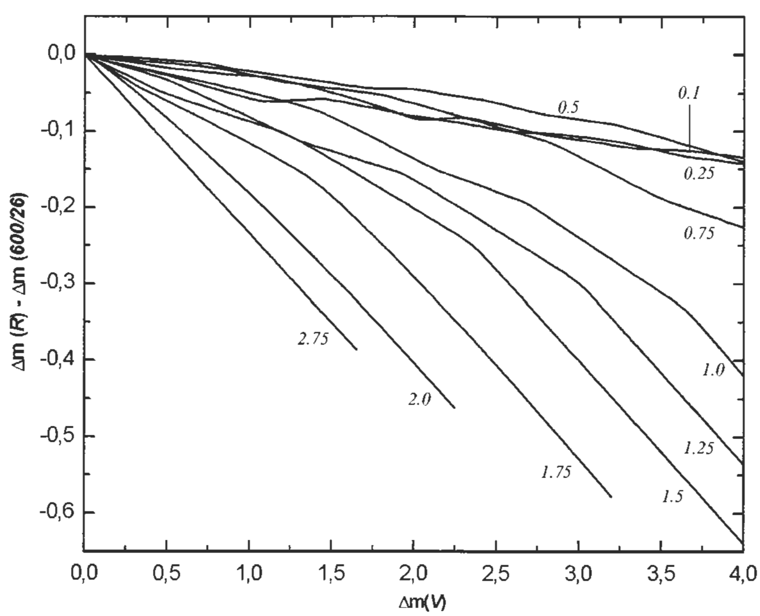

Figure 3: *The same as in Fig. 2 but for transition from the filter* 600/26 *to the* R *band.*

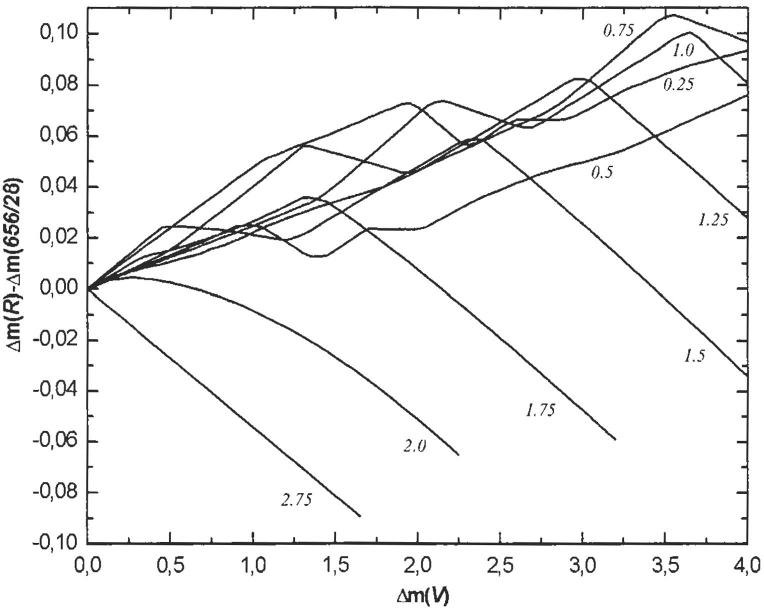

Figure 4: *The same as in Fig. 2, but for transition from the filter* 656/28 *to the R band.*

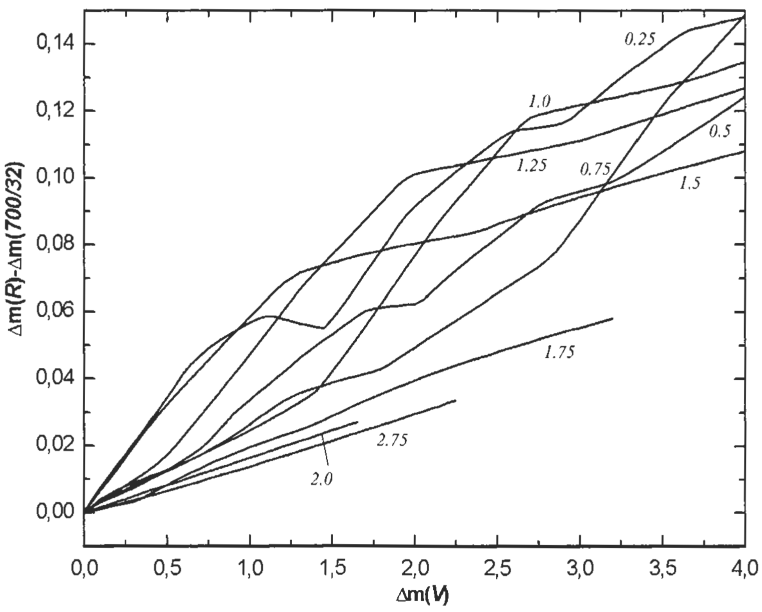

Figure 5: *The same as in Fig. 2, but for transition from the filter* 700/32 *to the R band.*

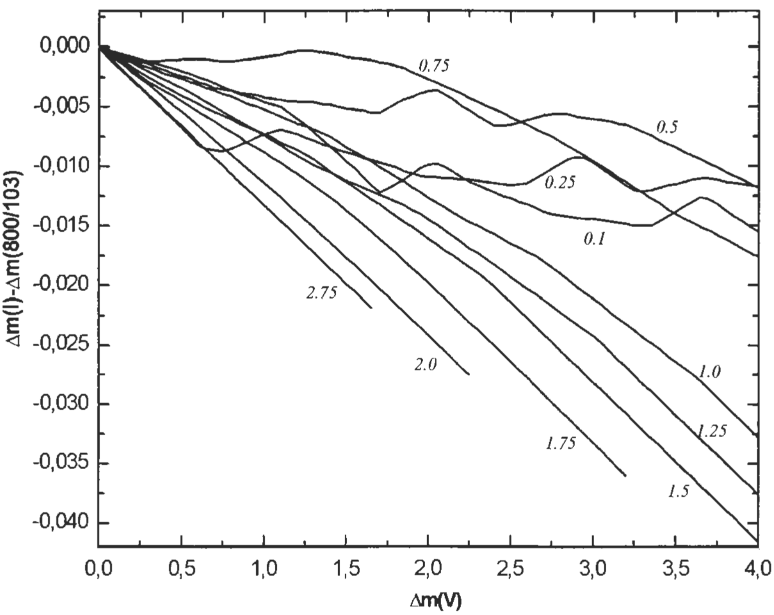

Figure 6: *The same as in Fig. 2, but for transition from the filter* 800/103 *to the I band.*

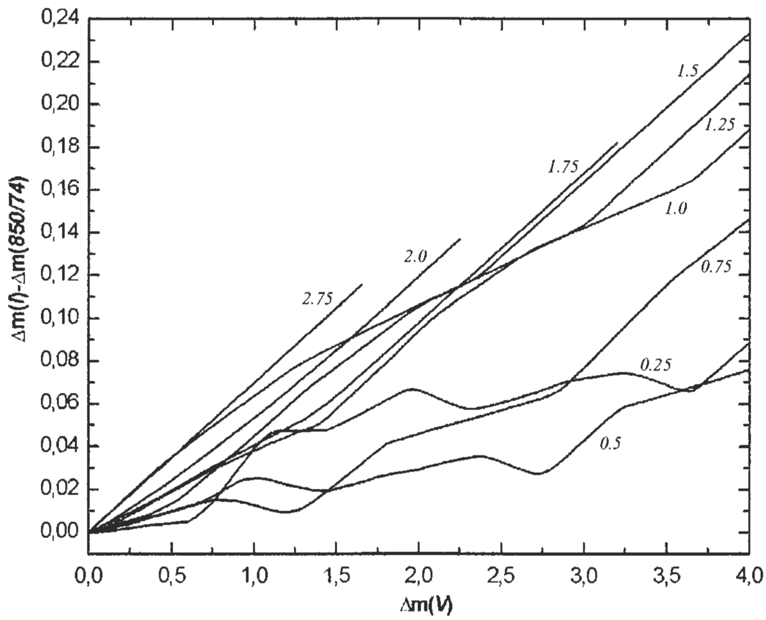

Figure 7: *The same as in Fig. 2, but for transition from the filter* 850/74 *to the I band.*

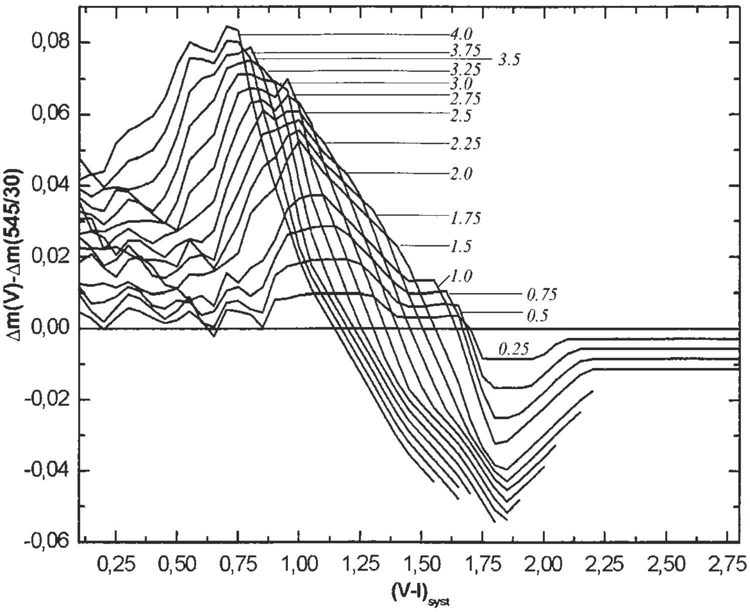

Figure 8: *The same as in Fig. 2, but the color* $(V-I)_{syst}$. *is plotted on the abscissa. The family of the graphs corresponds to different* Δm_V, *whose values are indicated.*

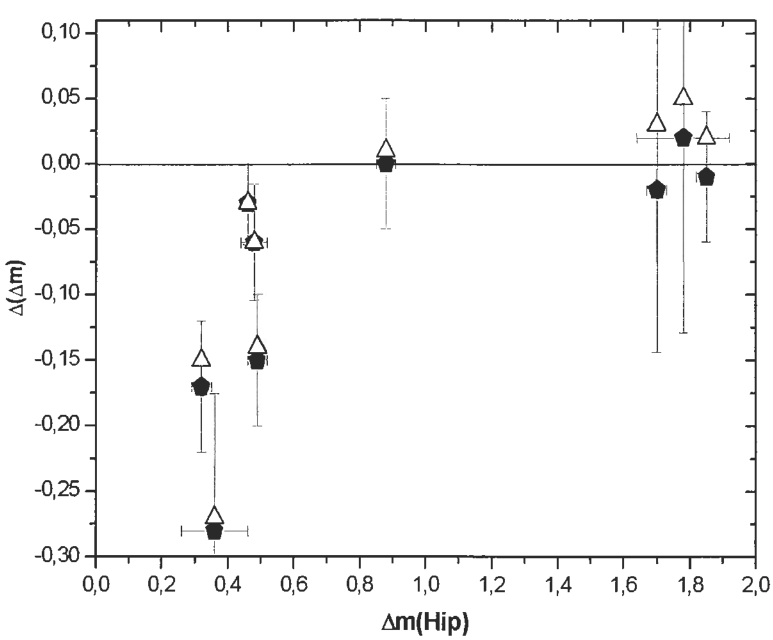

Figure 9: *Comparison of* Δm: *a) in the filter 545/30 and* $\Delta m(Hip)$ *(open symbols); b) transformed from the filter 545/30 to the system Hipparcos and* $\Delta m(Hip)$ *(filled symbols).*

As the final value of the magnitude difference one may take the value $\Delta m_V = \Delta m_{545/30} + \delta^1$, where δ^1 is the correction value in the filter with $\lambda_{eff} = 545nm$ found from the approximated value of Δm_V^1. On its basis one can find the final correction value δ with the proclaimed accuracy.

6. Influence of systematic errors

As any procedure, the algorithm applied to calculating the magnitude difference on the basis of BTA speckle interferometric observations, is burdened with systematic or other errors. Their detailed analysis is not the aim of the present paper, and we give only an estimation of their influence.

The only mission making mass and homogeneous estimations of the magnitude difference of binary stars with a separation less than 1″ is that of Hipparcos. The photometric band in which observations were carried out is close to the V band (ESA 1997). Observations of the same stars conducted in the filter with $\lambda_{eff} = 545nm$ and with Hipparcos can be used to take into account the rest of the errors. An attempt to do this was made in the paper by Balega et al. (2002). However, from their results we can not separate the effect of the difference in photometric bands of the interferometer and the satellite from the influence of other errors.

Corrections for transition from the interferometer band with $\lambda_{eff} = 545\,nm$ to the Hipparcos band were calculated by the above method using the data from (ESA 1997). Then a sample of common stars was formed with a separation of $0.2'' \leq \rho \leq 0.5''$ and an error of magnitude difference determination of 0.15^m. Restrictions on the distance between the components was caused by the fact that results of speckle interferometric observations for wide pairs may produce unreliable data because of cutting off the image by the frame window, whereas for close pairs Hipparcos results have a considerable error caused by the small size of the satellite telescope aperture (Balega et al. 2002).

For this sample the Δm was calculated using the corrections of the transfer from the interferometer band to the band of Hipparcos. Then the difference between the "theoretical" and real magnitude differences will be a residual neglected error.

For the sample stars, Fig. 9 displays the difference between the observed and "theoretical" $\Delta m(Hip)$ (filled symbols), and also the difference between the observed $\Delta m(Hip)$ and $\Delta m(545/30)$ prior to the reduction. The following may be noted.

Firstly, for system with a considerable magnitude difference ($\Delta m > 0.8^m$) the influence of systematic errors is insignificant, and allowance only for the correction δ makes it possible to obtain the magnitude difference to an error of $0.01^m ... 0.03^m$, which is sure to depend on observational conditions and object brightness and may be appreciably greater.

Secondly, for systems with the components of close luminosity there are significant distinctions of the theoretical magnitude difference after the reduction and measured directly by the satellite Hipparcos Δm. The value of these differences may reach $0.1^m ... 0.2^m$, whereas the corrections of the transition between photometric systems for small (Δm) do not exceed a few hundredths of the magnitude. For small Δm the systematic error in a linear approximation by the least-squares method is described by the law

$$\delta_{syst} = 0.26(\pm 0.12) \cdot \Delta m(V) - 0.21(\pm 0.06), \qquad (5)$$

$$\Delta m(V) < 1^m.$$

However, it should be emphasized that from the data available it is impossible to ascertain a reliable value of the systematic correction, and the presented values are only approximated. The linear approximation of the whole range of Δm yields

$$\delta_{syst} = 0.07(\pm 0.03) \cdot \Delta m(V) - 0.12(\pm 0.03), \qquad (6)$$

which is in agreement with the relationship obtained (Balega et al. 2002) in an analogous manner, which in used terms should be given by the law

$$\delta_{syst} = 0.06 \cdot \Delta m(Hip) - 0.13. \qquad (7)$$

Thus, the correction for the transfer from the photometric system of the interferometer to the standard one consists of two parts — δ (2) and δ_{syst} (6) which take account of the difference of bands themselves and errors of the method, respectively. And if δ (2) could be determined with an error of $0.01^m ... 0.02^m$, the δ_{syst} requires a detailed analysis to attain the desired accuracy of the method.

7. Conclusions

We propose matrices of reduction coefficients for transformation of the magnitude difference from the speckle interferometer to the VRI photometric system, where the input data for finding corrections are the magnitude difference of the components in the V band Δm_V and the color index of the system $(V - I)_{syst}$. The coefficients were determined with an accuracy no worse than 0.02^m ($\approx 30K$ in a temperature scale). Apart from this, estimates of systematic errors of the technique were made.

Evidently, the corrections could also be applied to triple stars and systems of higher multiplicity.

The determination of the magnitude differences of the components in the VRI filters of the system as a whole will make it possible to estimate individual stellar magnitudes and colors of stars and hence parallaxes and physical characteristics of each of the system components.

8. Appendix

Below the coefficients of cubic polynomial approximation of the relationships $\delta(\Delta m_V, (V-I)_{syst}$ determined by the least-squares method are presented. The approximation accuracy is 0.02^m. The value of δ is found as

$$\delta = a \cdot \Delta m_V + b \cdot \Delta m_V^2 +$$
$$+c \cdot \Delta m_V^3 + +d \cdot (V-I) + e \cdot (V-I)^2 +$$
$$+f \cdot (V-I)^3 + g \cdot \Delta m_V \cdot (V-I) +$$
$$+h \cdot \Delta m_V \cdot (V-I)^2 + i \cdot \Delta m_V^2 \cdot (V-I). \quad (8)$$

By virtue of the complex character of the surface $\delta(\Delta m_V, (V-I)_{syst}$, the coefficients $a...i$ were calculated separately for several intervals of Δm_V and $(V-I)_{syst}$. The coefficients $a...i$ and the boundaries of the region inside which approximation by the appropriate polynomial was performed are indicated for each filter in Tables 2–7.

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Table 2: *Coefficients of approximating relations* $\delta(\Delta m_V, (V-I)_{syst})$ *of polynomials for the filter 545/30.*

Δm_V	[0.0; 4.0]	[0.0; 1.5]	[1.5; 4.0]	[0.0; 4.0]
$(V-I)$	[0.1; 0.8]	[0.8; 1.5]	[0.8; 1.5]	[1.5; 2.8]
a	0.0000	−0.0004	0.0000	0.0001
b	0.0029	0.0738	0.0050	−0.0183
c	−0.0002	−0.0336	−0.0004	0.0036
d	0.1079	−0.1745	0.2781	0.1739
e	−0.3722	0.3126	−0.3066	−0.1625
f	0.3040	−0.1316	0.0818	0.0364
g	−0.0001	0.0000	0.0000	0.0000
h	0.0205	−0.0126	0.0070	0.0018
i	0.0014	−0.0008	−0.0096	0.0001

Table 3: *Coefficients of approximating relations* $\delta(\Delta m_V, (V-I)_{syst})$ *of polynomials for the filter 600/26.*

Δm_V	[0.0; 1.5]	[1.5; 2.5]	[2.5; 3.5]	[3.5; 4.0]	[0.0; 1.5]	[1.5; 4.0]	[0.0; 1.5]	[1.5; 4.0]	[0.0; 1.0]	[1.0; 4.0]
$(V-I)$	[0.1; 0.8]	[0.1; 0.8]	[0.1; 0.8]	[0.1; 0.8]	[0.8; 1.0]	[0.8; 1.5]	[1.5; 2.1]	[1.5; 2.1]	[2.1; 2.8]	[2.1; 2.8]
a	0.0004	0.0000	0.0000	0.0000	0.0003	0.0000	−0.0007	0.000	−0.0010	0.0000
b	−0.0619	0.0046	0.0272	0.0456	−0.0383	0.0143	0.1409	−0.0209	−0.5167	−0.1680
c	0.0260	−0.0069	−0.0109	−0.0141	0.0170	−0.0004	−0.0652	−0.0076	0.3753	0.0939
d	−0.0855	−0.6713	−1.5985	−2.7424	0.1707	0.0595	−0.2877	0.2568	0.0716	0.2787
e	0.2327	1.8986	4.4700	7.0357	−0.2892	−0.1977	0.3292	−0.1638	−0.0699	−0.2775
f	−0.1728	−1.0436	−1.6278	−1.1149	0.1170	0.07463	−0.0913	0.0429	0.0148	0.0498
g	−0.0002	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
h	0.0165	−0.2971	−0.8736	−1.6041	−0.0289	0.0181	−0.0621	−0.0944	0.0034	0.0515
i	0.0036	0.0594	0.1117	0.1745	−0.00450	−0.0383	−0.0066	0.03583	−0.0292	−0.0918

Table 4: *Coefficients of approximating relations* $\delta(\Delta m_V, (V-I)_{syst})$ *of polynomials for the filter 656/28.*

Δm_V	[0.0; 1.0]	[1.0; 2.5]	[2.5; 4.0]	[0.0; 2.5]	[2.5; 4.0]	[0.0; 4.0]
$(V-I)$	[0.1; 0.8]	[0.1; 0.8]	[0.1; 0.8]	[0.8; 1.5]	[0.8; 1.5]	[1.5; 2.8]
a	0.0004	0.0000	0.0000	−0.0002	0.0000	−0.0002
b	0.1070	0.0008	0.0074	0.0387	0.0441	0.0730
c	−0.0914	0.0033	−0.0008	−0.0094	−0.0077	−0.0084
d	−0.0118	0.4639	0.3438	−0.1077	−0.4258	0.0941
e	0.0498	−1.4208	−1.2157	0.1888	0.6612	−0.0786
f	−0.0147	0.9847	0.9490	−0.0749	−0.1718	0.0162
g	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000
h	−0.1292	0.1239	0.0399	−0.0028	−0.0761	−0.0076
i	0.0718	−0.0306	−0.0019	−0.0049	0.0064	−0.0267

Table 5: *Coefficients of approximating relations $\delta(\Delta m_V, (V-I)_{syst})$ of polynomials for the filter 700/32.*

Δm_V	[0.0; 4.0]	[0.0; 4.0]	[0.0; 4.0]	[0.0; 4.0]
$(V-I)$	[0.1; 0.5]	[0.5; 0.8]	[0.8; 1.5]	[1.5; 2.8]
a	−0.0001	−0.0002	−0.0001	0.0000
b	0.0265	0.0147	0.0339	0.0294
c	−0.0045	−0.0053	−0.0032	−0.0012
d	0.3082	0.4407	−0.2262	0.1960
e	−1.1234	−1.1678	0.3783	−0.1747
f	1.0551	0.8324	−0.1508	0.0378
g	0.0000	0.0000	0.0000	0.0000
h	0.0286	−0.0712	0.0170	0.0052
i	−0.0064	0.0310	−0.0171	−0.0148

Table 6: *Coefficients of approximatingrelations $\delta(\Delta m_V, (V-I)_{syst})$ of polynomialsfor the filter 800/103.*

Δm_V	[0.0; 4.0]	[0.0; 4.0]
$(V-I)$	[0.1; 0.7]	[0.7; 2.8]
a	0.0000	0.0001
b	−0.0001	−0.0037
c	−0.0000	0.0007
d	−0.1231	0.0201
e	0.4582	−0.0233
f	−0.4074	0.0057
g	0.0001	0.0000
h	−0.0049	−0.0004
i	−0.0002	−0.0008

Table 7: *Coefficients of approximating relations $\delta(\Delta m_V, (V-I)_{syst})$ of polynomials for the filter 850/74.*

Δm_V	[0.0; 4.0]	[0.0; 1.5]	[1.5; 4.0]	[1.5; 4.0]	[0.0; 1.5]	[0.0; 4.0]
$(V-I)$	[0.1; 0.4]	[0.4; 1.0]	[0.4; 0.8]	[0.8; 1.5]	[1.0; 1.5]	[1.5; 2.8]
a	0.0001	0.0003	0.0001	0.0000	0.0004	−0.0001
b	0.0206	0.0079	−0.0112	0.0144	0.0038	0.0245
c	−0.0041	0.0117	0.0028	−0.0015	0.0261	−0.0011
d	0.1143	0.3385	0.8817	−0.1837	0.0028	0.0285
e	−0.6324	−0.9164	−2.5802	0.3380	−0.0192	−0.0195
f	1.3729	0.5863	1.7629	−0.1240	0.0104	0.0032
g	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000
h	−0.0661	0.0755	0.1004	−0.0038	0.0480	0.0108
i	0.0027	−0.0519	−0.0033	0.0023	−0.0448	−0.0081