SYSTEMATIC ERRORS OF HIGH–PRECISION PHOTOMETRIC CATALOGUES

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Abstract. A very accurate imitation of Hipparcos and Tycho Hp, B_{T}, and V_{T} magnitudes was made using W, B, V, R magnitudes from the Tien Shan photometric catalogue. The calculated magnitudes were compared to the observed ones. It is shown that there are systematic differences between calculated and observed magnitudes. The systematic errors are supposed to be bound up with the sky scanning procedure on the Hipparcos satellite. Polynomials in powers of coordinates have been proposed to take into account the systematic errors. 6558 stars have been found to be appropriate high-precision photometric standards.

1. Introduction

It is clear that the realization of such projects as FAME and GAIA requires a great number of high-precision photometric standards with good coverage all over the celestial sphere. Every photometric catalogue contains various systematic errors which may be avoided only by comparing different catalogues. To solve this problem, the data and experience which were obtained while carrying out the Hipparcos project are of great importance. The experience acquired allows a number of systematic errors to be avoided in the projects to come, both in photometry and astrometry.

The current study is devoted to analysis and comparison between the up-to-date high-precision photometric catalogues, the ground-based 'Catalogue of $WBVR$ Magnitudes of Bright Northern Stars' Kornilov et al. (1991) (hereafter, WBVR catalogue), and the Hp, B_{T}, and V_{T} photometric magnitudes obtained in the space experiments Hipparcos and Tycho (ESA, 1997). From these, we have chosen a large number of stars which may be appropriate for a dense network of high-precision photometric standards. We have selected the stars which are available both in the WBVR catalogue and in the Hipparcos and Tycho data unless any evidence for their variability or binarity has been present.

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2. Intrinsic Accuracy of the WBVR Catalogue and the *Hp*, B_T, V_T Magnitudes

The WBVR catalogue contains approximately as many as 13 500 objects located between the north celestial pole and the declination of 15°. Each of these objects has got the magnitudes measured in four photometric bands: W, B, V, and R. The catalogue is available at http://lnfm1.sai.msu.ru/lnfm/eng/catal. More detailed description of the bands can be found in the introductory remarks of the catalogue itself.

Observations were carried out at the high-altitude observatory, nearby the town of Alma-Ata in Kazakhstan, 3000 m above the sea level, in the Trans-Ili Ala-Tau which is the northern ridge of the Tien Shan. Most objects were measured four times each, twice during one observational night and twice during another one.

We estimated independently the intrinsic accuracy of the catalogue. The root-mean-square (r.m.s.) errors of averaged magnitudes are equal to $\sigma_{\overline{W}} = 0^m.0066$, $\sigma_{\overline{B}} = 0^m.0038$, $\sigma_{\overline{V}} = 0^m.0035$, and $\sigma_{\overline{R}} = 0^m.0042$. The r.m.s. errors are intrinsic errors, that is, the lower limits to the total errors of stellar magnitudes measured in a given photometric band.

The published Hipparcos data contain, along with mean measurements, individual determinations of stellar magnitudes estimated in each passing of an object through a field of view (as for the Tycho catalogue, we used individual estimates but for about 35 000 stars available on the CD ROM). Therefore, as in the case of the WBVR catalogue, we calculated deviations of every measurement of every star from its mean values, and derived the standard errors for the bands Hp, V_T and B_T. It turns out that the r.m.s. errors of averaged magnitudes are equal correspondingly to $\sigma_{\overline{Hp}} = 0^m.0008$, $\sigma_{\overline{B_T}} = 0^m.0052$, and $\sigma_{\overline{V_T}} = 0^m.0039$. Our estimates of intrinsic accuracy of the WBVR and the Hipparcos catalogues are in good accordance with the results published by their authors.

3. Transformations Between Photometric Systems

To compare stellar magnitudes obtained in various photometric systems it is necessary to determine the transformation procedure between the systems. We derived empirical formulae which relate the Hp, B_T, V_T magnitudes to the V magnitudes and the $W-B$, $B-V$, $V-R$ color indices. AS the result of the comparison, a number of stars with rough mistakes of their magnitudes or with wrong identifications were excluded. Finally, as many as 6558 stars have been selected.

We searched then for the models representing the differences Hp–V, V_T–V, $B_T - B$ as functions of W, B, V, R magnitudes. We also have found inverse functions to approximate V and B magnitudes by Hp, V_T, B_T magnitudes:

$$(Hp-V)_{calc}=f_{Hp}(W,B,V,R),\quad (V-V_T)_{calc}=\varphi_v(Hp,V_T,B_T),$$
$$(V_T-V)_{calc}=f_v(W,B,V,R),\quad (B-B_T)_{calc}=\varphi_b(Hp,V_T,B_T),$$
$$(B_T-B)_{calc}=f_b(W,B,V,R).$$

To transform W, B, V, R magnitudes to Hp, B_T, V_T, we used a second order polynomial in V supplemented with a cubic polynomial in three color indices. While using higher order polynomials the sum of residual deviations squared did not seem to be minimized. B, V magnitudes were approximated by Hp, B_T, and V_T using the 5th order polynomials in color indices $B_T - V_T$ and $Hp - V_T$.

4. Inquiry of Residual Deviations. Coordinate–Dependent Systematic Errors

In our inquiry of residual deviations we expressed the differences of $Hp - V$, $V_T - V$, $B_T - B$ in terms of W, B, V, R. The dispersion of residual deviations exceeded significantly the sum of dispersions of intrinsic catalogue errors. It may be due to the systematic errors in the magnitudes independent of the color indices. We have suggested the presence of systematic errors dependent on celestial coordinates. Residual deviations can be, in principle, coordinate-dependent because intrinsic errors in the catalogues may be of instrumental origin or arise from procedure reasons. The new transformation equations were assumed to involve terms dependent on color indices and celestial coordinates (α-right ascension and δ-declination), as follows:

$$(Hp-V)_{calc}=f_{Hp}(W,B,V,R)+g^{Hp-V}_{WBVR}(\alpha,\delta),$$
$$(V_T-V)_{calc}=f_V(W,B,V,R)+g^{V_T-V}_{WBVR}(\alpha,\delta),$$
$$(B_T-B)_{calc}=f_B(W,B,V,R)+g^{B_T-B}_{WBVR}(\alpha,\delta).$$

Then we have analyzed the residual deviations again, and concluded:

1) The residual deviations, $\delta_{Hp,V} = (Hp-V)^{obs}-(Hp-V)^{calc}$, do not show any dependence on color indices. Their standard deviation is $\sigma_{(\delta_{Hp,V})} = 0^m.0048$.
2) The functions $g^{Hp-V}_{WBVR}(\alpha,\delta)$ (Figure 1) and $g^{V_T-V}_{WBVR}(\alpha,\delta)$ exhibit similar behavior.

This can be accounted for by the fact that both $Hp - V$ and $V_T - V$ contain V-magnitudes from the Tien Shan catalogue which may involve its intrinsic systematic errors. Nevertheless, the most noticeable peculiarity is located close to the coordinates $\alpha = 270°$, $\delta = +67°$. This is the region of the north ecliptic

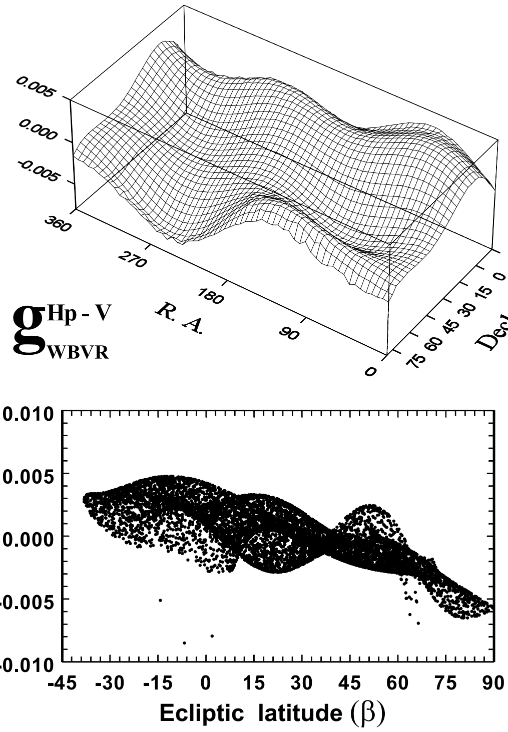

Figure 1. The systematic differences between Hp and V magnitudes as a function of celestial coordinates (g_{WBVR}^{Hp-V} in magnitudes).

pole. In the bottom panel of Figure 1 function g_{WBVR}^{Hp-V} is plotted versus ecliptic latitude. A slope of the function becomes steeper while approaching the ecliptic pole. However, along declination this effect is not seen.

The ecliptic pole was by no means a peculiar point when observing the stars from the WBVR catalogue. On the contrary, the procedure of scanning the sky with Hipparcos satellite leads to a symmetrical distribution of scans relative to the ecliptic.

The upper panel of Figure 2 shows the number of star observations in the Hipparcos catalogue versus ecliptic latitude for the north hemisphere. To construct the two panels of Figure 2 only 6558 stars have been used, selected as described above. The stars in the ecliptic area were observed in the minimum number of cases (50 − 100). In the zone of ecliptic latitudes $40° < \beta < 60°$ a number of star observations increases sharply reaching 250 on average. In the polar regions a number of observations decreases again and becomes equal approximately to 120. It is seen distinctly that the latitude line $\approx 46°$ divides the points into two groups. These groups resulted from the scanning procedure. At the bottom panel of the Figure 2 the mean Julian date of observation for every star is shown versus its ecliptic

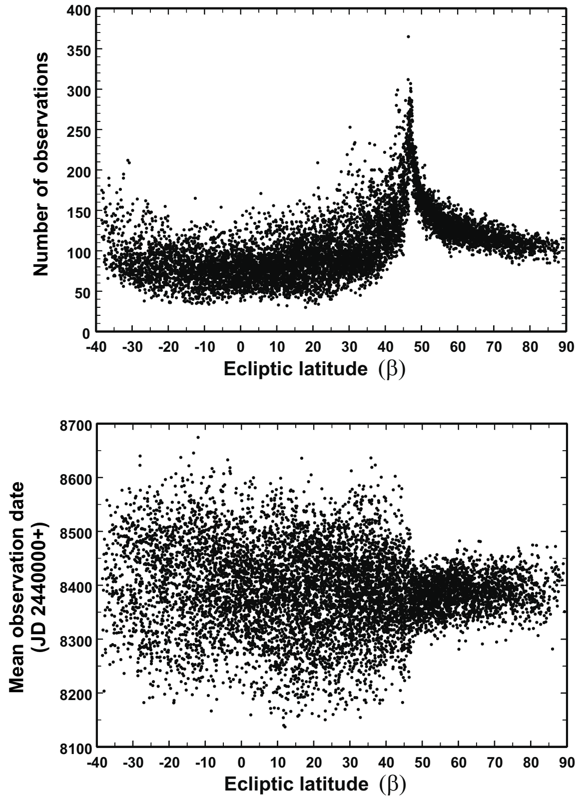

Figure 2. Properties of the Hipparcos catalogue, concerned with celestial coordinates. Upper panel: the number of observations of stars vs. ecliptic latitude. Bottom panel: the mean dates of observations of stars vs. ecliptic latitude.

latitude β. It is supposed that such a non-uniform distribution of observations may be a cause of systematic errors. Their amplitude is about $\pm 0^m.005$.

According to the inquiry of systematic differences between the catalogues based upon 6558 stars considered, these stars can be regarded as good candidates for high-precision standards. Taking into account the systematic errors, one can anticipate the systematic differences between the catalogues Hipparcos and WBVR to be $\leq 0^m.002$.

5. Discussion and Conclusions

One should not believe that the systematic errors derived in this study are negligible. The FAME and GAIA projects are aimed at determining coordinates and stellar parallaxes with an accuracy of some tens of microarcseconds. This implies that photometry of these stars should be carried out to the highest degree of accuracy.

For example, it is necessary to take into account such instrumental effects as residual off-axis aberrations depending on the wavelength. The presence of such aberrations is a common feature of optical systems, even of pure reflecting ones. The aberrations are responsible for the change of the position of the peak light intensity on a light-sensitive surface with the wavelength. To take this effect into account *one must know* the color indices of each star at least with an accuracy of $0^m.01$. Otherwise, systematic errors in positioning may approach $\pm 25\,\mu$as or even more, which is comparable to a supposed error in measuring parallaxes. Numerical simulation of the processes which might give rise to such errors is under way now in Moscow.

In our opinion, there exist *principal difficulties* to acquire accurate coordinates and accurate multicolor photometry simultaneously during one experiment. Furthermore, currently there is no proper system of multicolor photometric standards in the range from 8^m to 15^m. To attack this problem, a photometric survey of the sky is being planned in the Sternberg Astronomical Institute in collaboration with several other institutions of Russia. The project is aimed at determining accurate magnitudes of the stars brighter than 15^m in 10 or 12 bands from 2000 to 11 000 Å. The project named *LYRA* has been incorporated into a number of Russian experiments to be carried out at the International Space Station.

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