POSITIONAL MEASUREMENTS OF THE METEOR TV IMAGES

Yu.M. Gorbanev, S.R. Kimakovsky, E.F. Knyazkova

Astronomical Observatory of I.I.Mechnikov Odessa National University
Odessa, Ukraine
skydust@rambler.ru, keysi@nm.ru, skycomet@te.net.ua

ABSTRACT. We discuss the methods and software which is used for processing of the meteor TV images. Methods are based on the principles of the aperture CCD photometry. Software enables one to make processing of the observational material that was secured using TV methods with telescopic systems (field of view less that 1 angular degree), as well as with astrocameras of the wide field of view (field of view less 2-4 angular degrees, and even more than 50 degrees). We also elaborated method that allows one to identify operatively and to measure automatically rectangular coordinates within the image frame, as well as to calculate equatorial coordinates of the object using the Turner method and compiled stellar catalogues. This method was tested with observational material obtained with the help of TV meteor patrol within the period from 2003 to 2010 at Kryzhanovka station that belongs to Astronomical Observatory of Odessa National University. We performed an analysis of accuracy determination of the stellar images measurements. Software was tested in order to use it for the comet observations.

Key words: meteor, meteor stream, television observations, Terner coordinates reduction.

1. Methods and software

At present the sensitive CCD are commonly used in astronomical observations instead of photographic detectors. This caused the search for the new methods of the image processing and new software creation. In particular, the regular meteor patrol observations showed the necessity of the software creation which is adapted for processing of the observational material obtained via TV method [1, 2]. As a result, we created software ***PSF*** which gives a possibility to operatively identify stellar regions where meteor patrolling is made, automatically determine coordinates of the stellar images within the TV frame, and calculate equatorial coordinates of the object using the Turner method.

Software was created on the base of the licensed version of the Visual Basic 6.0 from Microsoft Visual Studio 6.0. As reference catalogues we used compiled catalogues based on SAO, Tycho-2, USNO A-2 and other catalogues. In more details this question will be considered in Sec.2. Pattern files contain the following parameters of the observational instrumentation: the actual field of view (in arcsec), mirror (telescope) or direct (astrocamera) image, scaling coefficient that corresponds to the instrument focal length. For each image from the database containing images of the registered meteor event, the name of the certain guiding star is assigned. Software makes selection of the reference stars from the indicated catalogue using the necessary for a given image guiding star, then it searches and identifies selected stars within the image. Identifications and measurements are performed in the averaged TV frame which is obtained from 50 individual frames (2 sec).

The method of the preliminary reduction of the observational material is described in details in [2]. This method is based on the differential aperture photometry that is used for determination of the rectangular coordinates, and Turner method, which is used to determine equatorial coordinates.

The Turner method is used for determination of the object position within the frame from the object rectangular coordinates in the frame system relatively the reference stars (for these stars their equatorial coordinates are known from catalogues). The Turner method gives the mathematical relation between the system of ideal coordinates of the reference stars that were previously calculated basing on their known equatorial coordinates, and the system of rectangular coordinates determined within the frame basing on the aperture photometry method.

Relation between the ideal coordinates ξ, η and measured rectangular coordinates x, y of celestial bodies can be written as power series (the system of the reducing Turner equations):

$$\begin{aligned} \xi &= ax + by + c + dx^2 + exy + fy^2 + \ldots \\ \eta &= a'x + b'y + c' + d'x^2 + e'xy + f'y^2 + \ldots \end{aligned} \quad (1)$$

Where $a, b, c, \ldots, a', b', c' \ldots$ – are the reducing coefficients which are called "frame constants". They can be found using the least square method and system of the separated Turner equations composed for the series of reference stars. Obtained in such way relations then can be used for transformation of the measured in the frame rectangular coordinates x and y of a given object into the ideal coordinates ξ и η. The latter ones are used to derive equatorial coordinates.

We use some modification of the aperture photometry for determination of the rectangular coordinates of the stellar images. In this case calculations are made for the sum of the pixel intensities inside some region. As a rule the summation is performed inside the circle. In our method the aperture radius is determined for each stellar image depending on the catalogued stellar magnitude of the star. For different instruments we introduce specific correction depending on focal length. If necessary, the aperture radius can be set manually by user itself. After the determination of the aperture radius one can calculate the mean background value for each star outside the aperture. All the points inside aperture with intensity value exceeding the background value by 3 σ belong to the stellar image. The photometric center of image can be calculated using the following formulae:

$$X = \frac{\sum(X_i * I_i)}{\sum I_i} \; ; \; Y = \frac{\sum(Y_i * I_i)}{\sum I_i} \qquad (2)$$

where X_i and Y_i are the rectangular coordinates of the pixels that belong to the stellar image, I_i - signal intensity for the corresponding pixels (in appropriate units). Processing is performed in the following way.

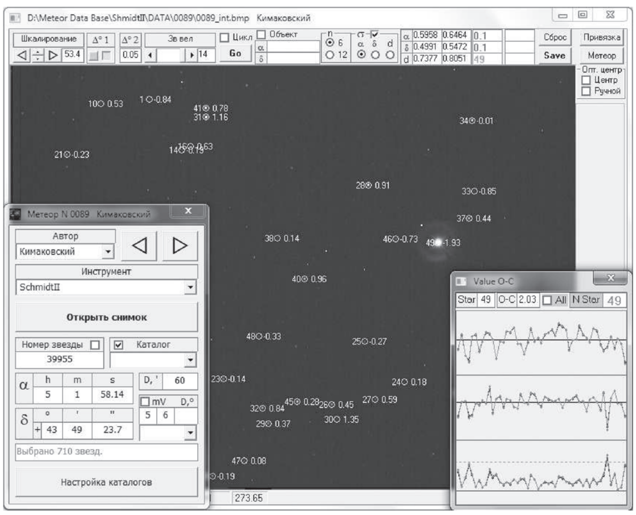

Figure 1: ***PSF*** interface.

After the starting ***PSF*** software user should be authorized. This is necessary to control the measurements which are made by each user. Then user has a possibility to choose the necessary instrumentation from the pattern file. Then after the loading of the added frame, the user indicates the reference catalogue and guiding star. The stars from the reference catalogue are selected (taking into account the size of the effective field for a given instrument) and then dispatched to the main menu window (Fig.1).

Equatorial coordinates of the stars from reference catalogue are recalculated into rectangular coordinates in the image frame system and displayed by the circles of the different diameters. Let us call such images as the measuring diagrams (MD). User manually performs approximate superposition of the MD centers with the reference stars. At this stage the limiting stellar magnitude can be set. In this case an identification and superposition can be performed only for those reference stars whose magnitude does not exceed the limiting one.

After this, the photometric centers are calculated automatically for each star using the Eq. 2, and equatorial coordinates are calculated with the 6 and 12 constants of Turner method. Simultaneously the errors of the coordinates of the measured reference and control stars are calculated. The results of the measurements and calculations are displayed in the corresponding windows (see Fig.1). In particular, in the left lower corner (Fig.1) the resulting plot shows the errors found for control stars along the right ascension, declination, and also total errors. These relations enable one to identify the wrong orientation of the MD images: at the error plot there could be recognized some bias along one of the coordinates. Thus, the user may control the errors in the plot along each coordinate, as well as taking into account the value of the mean errors (α, δ and total) calculated using reference and control stars the user can correct the position of aperture diagrams of the stars with a fixed step on the rotation angle and coordinates, and by this making the accuracy of the calculations much better. By analyzing the value of error along each coordinate and total error (three plots), the user can also exclude the stars showing large errors. Large errors arise, first of all, because of the wrong orientation of the catalogued stars relatively to the stellar images, secondly, the source of the large errors is the distortion of the stellar images in the frame caused by the Earth's atmosphere, thirdly, the errors can arise as a result of the hot pixels of CCD. As a rule, the largest errors are typical for the most faint and most bright stars. For the former ones, the reason is the low number of pixels forming the image, for the latter ones - the flickering effect.

In that case when geometrical center of the effective field of CCD does not coincide with the optical axis of the system, before calculations it is necessary to search for the optical center of an image. This can be done automatically with a fixed step. The optimal position will be found even if the optical center is outside the frame. For this one needs to use the mean errors for control stars. The optical center position can be also set manually. If optimal values of parameters are selected, then the result will be quite accurate.

Using ***PSF*** one can measure rectangular coordinates of the comet and asteroid images, and then to calculate their equatorial coordinates. During the processing one can also calculate the errors for control stars that are situated in the frame in vicinity of the meteor trace. They are used for calculation of the equatorial coordinates of the large circle pole of the meteor trajectory.

As a result we obtain the file that contains calculated equatorial coordinates and measured rectangular coordinates, coefficients of the Turner method, the errors of determination of the reference and control stars coordinates, as well as other characteristics of the stellar images. File also keeps information about user and applied stellar catalogue that gives a possibility to perform the further analysis of the measurements and calculations made.

PSF enable one to work also with FTP (File Transfer Protocol), and to save measurements at the remote server. In this case, the result of processing immediately becomes available for other users. This afford a possibility to perform processing using remote computers (for example, this is important while performing the preliminary reduction of the observational material at the patrol stations, or if the different remote users are working simultaneously with the same material).

2. Stellar catalogues

Positional measurements and photometric analysis of the meteor images can be made with a highest precision if the reference stellar catalogues containing positions, photometric and spectral characteristics are selected correctly. In our case we used the following catalogues:

1.**SAO** (Smithsonian Astrophysical Observatory Star Catalog) /Publ. of the Smithsonian Institution of Washington, D.C. 4652 (1966)/ This catalogue contains positions of the stars on J2000 epoch, V and B stellar magnitudes, spectral classes and proper motions;

2.**Hipparcos** (Hipparcos Input Catalogue, Version 2) /Bull. Inf. CDS 43, 5 (1993):/This catalogue contains the high-precision positions of the stars, stellar V and B magnitudes (catalogue photometric system), spectral information, proper motions;

3.**Tycho-2** (The Tycho-2 Catalogue) /Astron. Astrophys. 355, L27 (2000)/ - high-precision stellar positions, V and B magnitudes, proper motions;

4.**USNO A2** (The PMM USNO-A2.0 Catalogue) / US Naval Observatory Flagstaff Station (1998)/ contains accurate positions of the stars, R and B stellar magnitudes.

Catalogues AGK3 /Astron. Astrophys. Suppl. Ser. 16, 345 (1974)/ and PPM (Positions and Proper Motions - North & South) / Astron. Astrophys. Suppl. Ser. 74, 449 (1988)/ were excluded from consideration as quite old sources, since the more recent catalogues are based on the more accurate data provided by satellites. The catalogue ACT (The ACT Reference Catalog) and similar ones were also ignored as being based on Tycho-2 catalogue and some ground-based observations that are not more precise than the data from Tycho-2 catalogue.

Selection criteria and analysis of used catalogues were the following. First of all, we need not astrometrical precision of the stellar positions: it is clear that the accuracy of the rectangular coordinates measurements results in equatorial coordinates determination with a precision not better than 1 arcsec. The same requirements are valid for the stellar magnitude accuracy (accuracy of 0.1^m is quite sufficient for our aim). All the above-mentioned catalogues satisfy to these criteria. For the photometry B and V magnitudes of the reference stars should be available. The data in both these filters are present in the most of listed catalogues. For SAO catalogue instead of V magnitude one can use the very close photographic magnitude, and for USNO-A2 catalogue one can change V magnitude to R magnitude. Considering the required for our aim accuracy such a substitution is quite justified. Availability of the spectral information is desirable, of course, but not necessary, since an analysis of the spectral characteristics is needed for some small tasks, but not for the extensive photometric and positional measurements of the meteor images.

In addition to the listed original catalogues we also created two compiled catalogues containing information about equatorial coordinates of the stars and their B and V magnitudes. These catalogues fit to our requirements concerning the positional and photometric characteristics of our measurements. These two compiled catalogues are: Hipparcos + Tycho-2 and Tycho-2 + USNO-A2. This enables one to increase the total number of the reference stars.

We should note that our optical devices do not allow us to register stars fainter than 13.5^m in V-band, therefore we have restricted the data from used catalogues up to 15^m (i.e. with some reserve in order to have a possibility to estimate the qualitative tendency in our analysis).

Very strict requirement is a necessity to have the great number of the faint stars (fainter than 10.5^m in V-band). It is even more important when the data obtained with Schmidt (field of view is about 0.5 square deg.) are reduced. To apply this criterion we have constructed the distribution in the available bands for all catalogues (Fig.2). As one can see the two catalogues Tycho-2 and USNO-A2 (as well as two compiled catalogues based on them) are most abundant

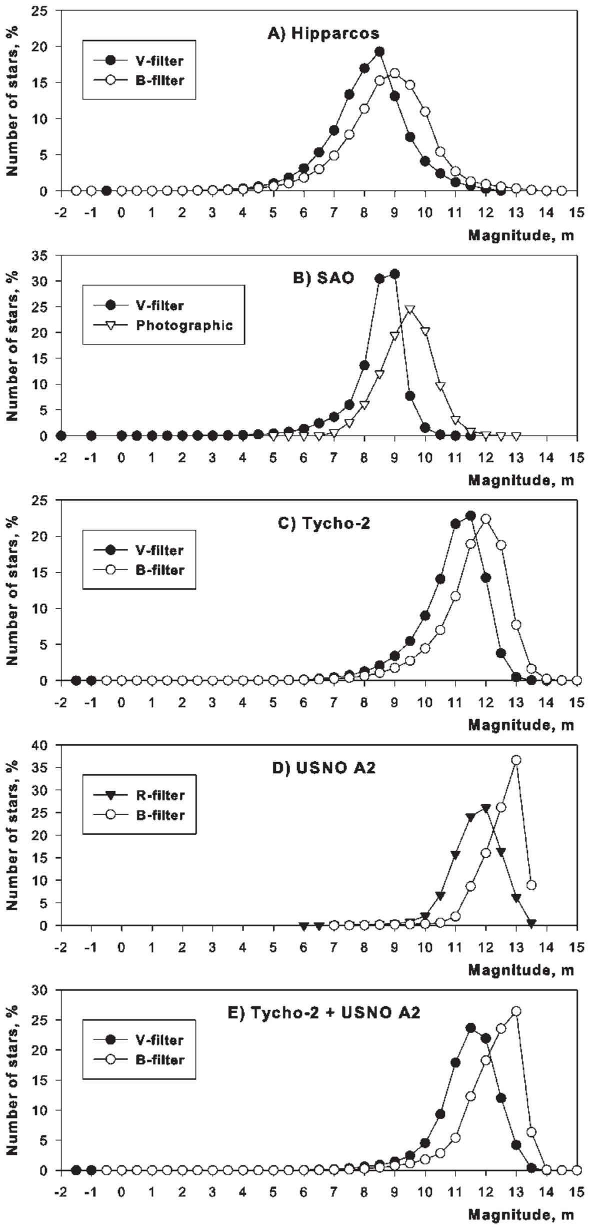

Figure 2: Percentage distribution of the stellar magnitudes in different bands for used catalogues.

in faint stars (plots C and D, and E and F respectively). Thus, having made a preliminary analysis of the plots in Fig.2, one can conclude that for meteor observations performed with Schmidt telescope (Turner method and photometry of the meteor trajectories) it is better to use these above mentioned catalogues. For observations which are performed with the wide-field view (about 2.5 square deg.) cameras with objective lens KO-140 SAO and Hipparcos catalogues can also be used since the very faint stars are not used in this case.

The next requirement is the high density of stars in

Table 1: The mean catalogue values of the star density (in 1 square degree).

Catalogue	Mean value
Hipparcos	2
SAO	4
Tycho2	39
Hipparcos + Tycho-2	40
USNO A2	72
Tycho-2 + USNO A2	112

the square degree. Fig.4 presents the distributions the total number of the stars from all sky with a step of 1 square degree (we call such a distribution as "density map"). In particular, for all catalogues one can note the clear tendency of the density increase along the ecliptic that testifies about the observational selection. We did not show in Fig.4 the density map for Hipparcos catalogue because it qualitatively resembles that of SAO catalogue (plot A), while the density along the ecliptic is even lower. We also do not present the density map for the USNO-A2 catalogue because qualitatively it is the same as for the corresponding compiled catalogue (plot C) where more clearly is seen the density inhomogeneity, in other words some "platform-like" distribution which is caused by the specific way of this catalogue creation by the combining of the space and ground-based observations. In the density map we also show the position of the centers of obtained images in equatorial coordinates. As one can see we often carry out our observations within those regions where the stellar density provided by SAO catalogue (and even more so by Hipparcos catalogue) is clearly insufficient. Table 1 lists the mean values of the stars in the square degree.

This value for the compiled catalogues should be decreased by about 50-70% because of the practically the same positions of the stars that are presented in the base catalogues used for the compilation. About 30-50% additional stars can be included from the ground-based surveys (in some cases for our aim it is enough to use such stars that were excluded from the more recent catalogues because of the lower accuracy of their atrometric characteristics). Selection and exclusion of the same stars from compiled catalogues is made by ***PSF*** software at the direct measurements of each image. The semi-automatic regime is also available.

Having analyzed the results of our measurement one can note that we use the following resources of catalogue selected for observational program: about 90% of the all number of available stars if observations are made with Schmidt telescope and up to 40% if astrocamera with objective lens KO-140 is used. Thus, the high density of the stars at the square degree is an important factor which is necessary for the high-quality data reduction.

As to the distribution of the spectral characteristic of the stars presented in our reference catalogues, their per cent ratio is showed in Fig.3.

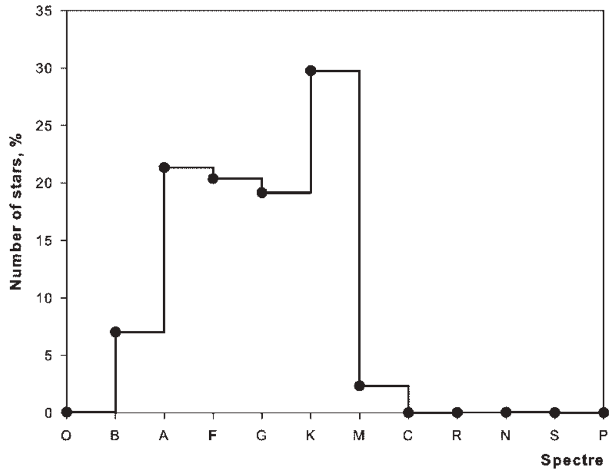

Figure 3: Distribution of the spectral characteristics for the stars from SAO catalogue.

Below we give some technical description of the catalogues used for the data processing. We created catalogues which are based on the primary files that are available (free access) at the web-page VizieR Catalogue Service (http://vizier.u-strasbg.fr/). For the most of the catalogues they are the text files, for the USNO-A2 catalogue they are binary files because of its big size (nowadays this catalogue is completely available at the abovementioned web-page). Using the file descriptions we selected only that information which is necessary for our observation, namely: equatorial coordinates of the stars, proper motions, spectral data, magnitudes of the stars in different band. As we mentioned above, from USNO-A2 catalogue we excluded all information about the stars fainter than 15^m (V-band).

All used catalogues were transformed in uniform format MS Access DBMS which enable one to perform a quick search inside the catalogue using the broad possibilities of SQLanguage. To accelerate the search process we divided the data on hour belts (24 tables inside of each database), and also calculated equatorial coordinates with fractional part. Program part is organized as VB language module with the help of ADO 2.8 technology. This module can be used both independently, and a part of ***PSF***. Used by us the storing format of the reference catalogues allow one to easy perform an analysis of the selected samples.

Let us make the short analysis of the measurements that are obtained using the selected reference catalogues.

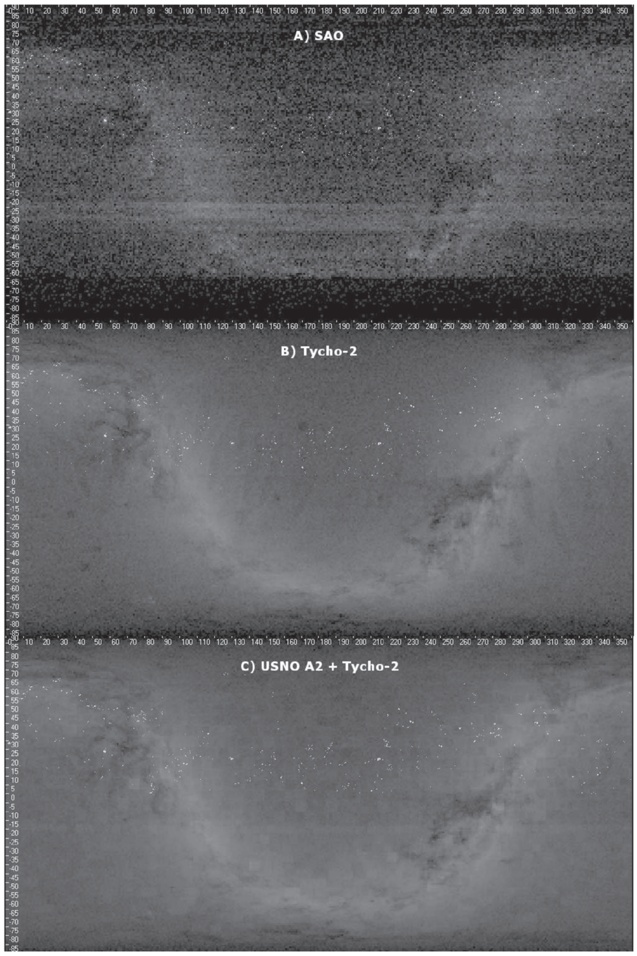

Figure 4: Stellar density as it is represented by the used catalogues. Dots - positions of the centers of the frame regions. Axes - equatorial coordinates.

3. Statistics of observations

Fig.5 shows the mean-square deviations for the reference stars for different catalogues and both observational instruments for more than three thousands meteor images depending on the stellar V-band magnitude. One can immediately note the obvious tendency: a decrease of the mean-square deviation with an increase of the stellar magnitude ("brightness equation"). For the brighter stars error is connected with their larger-scale and structured images. This significantly hampers measurements and worsens the quality of the processing (see Sec.1). For the observations performed with Schmidt telescope (the plots A, B, C) one can conclude that the most appropriate range of the reference stars magnitudes begins with $+6^m$. As to observations obtained with astrocamera (KO-140 objective lens), the plots D, E, F show that there one can trace one more tendency: for the reference stars fainter than $+9^m$ errors suddenly increases. This is caused by that fact that faint stars cannot be registered with this astrocamera, therefore during the image processing the faint stars are either cannot be measured, or it can be done but with a significant error. Since ***PSF*** enables one to determine the position of the reference stars in semi-automatic regime, for such stars user often selects either bright intensities of the background, or hot pixels (in some cases even defects of the images). Naturally, such stars are then excluded from analysis (because of the large value of mean-square error, or because of the limiting magnitude criterion). The plot gives concrete recommendations to users about the range of the stellar magnitudes of the reference stars that can be used (taking into account the instrumental characteristics applied for observations).

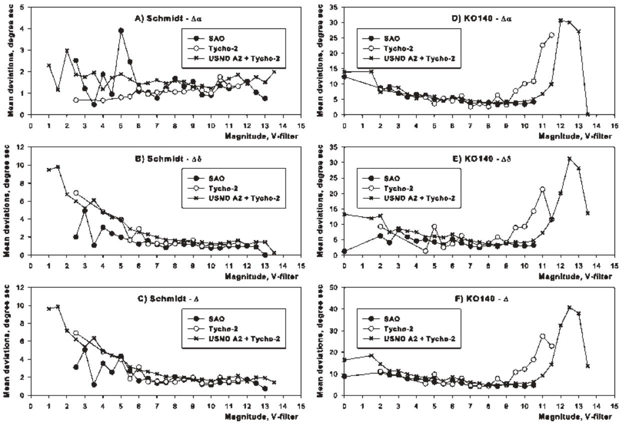

Figure 5: Mean-square deviations of the reference stars as a function of the stellar magnitude in V-band (along the right ascension and declination) for each reference catalogue and each instrument.

In Fig.6 we show maximum mean-square deviations of the reference stars (the same data as in Fig.5). It is clearly seen that for both instruments more bright stars show large deviations. The reason in this case is the same as for mean-square deviations in Fig.5. Similar situation (as for the mean-square deviations for the stars fainter than $+9^m$) also takes place for the data obtained with KO-140 (see plots D, E, F). One can also note that even for observational data obtained with Schmidt telescope the maximum errors attributed to the Tycho-2 and USNO-A2+Tycho-2 catalogues (particularly to the latter one) are larger than deviations resulting from SAO catalogue. Therefore such plots can be used for indirect estimate of the quality of positional data in the reference catalogues, and moreover they can be important for corresponding recommendations about some details of the data reduction process. We recommend using SAO catalogue as a reference one for the processing of the data obtained with KO-140 objective lens (if the number of stars within the field of view is quite enough). This is because the range of the stellar magnitudes covered with KO-140 is the same as that available in SAO catalogue. Images obtained with Schmidt telescope can be reduced only by using USNO-A2+Tycho-2 catalogue (this combination is abundant in faint stars, but it does not guarantee high accuracy of calculated equatorial coordinates).

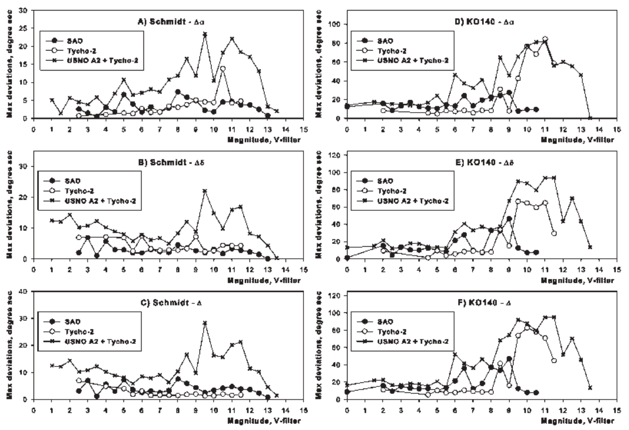

Figure 6: Maximum mean-square deviations as a function of the stellar magnitude in V-band (along the right ascension and declination) for each reference catalogue and each instrument.

Table 2 lists the mean-square deviations for the both instruments and for the three frequently used catalogues. N_m - the number of observed regions containing the meteor images, N_s - the number of the stars, σ_α (right ascension), σ_δ (declination) and σ (total) - the mean-square deviations of the reference star coordinates. The tendency mentioned above is confirmed (see Fig.6): the highest precision can be achieved using SAO as reference catalogue (which has a deficiency of the faint stars).

The content of Fig.7 is the further recommendation of using the SAO catalogue for the photometric analysis of the observations obtained with KO-140, and USNO-A2+Tycho-2 catalogue for the photometric analysis of the data gathered with Schmidt telescope.

In addition we show the distribution of the mean-square deviation across the optical field of our instruments (at the first approximation they can be considered as being uniform). This indicates that we correctly selected the method of the data reduction and testifies that our optical systems have the good quality.

Finally, we show percentage distribution of the module of the mean-square deviation of the reference star equatorial coordinates for different catalogues (Fig.8).

As one can see, the larger the error, the lower the percentage of the stars. For the great majority of the stars observed with Schmidt telescope the error value does not exceed 2-3 arcsec, while for the data obtained with KO-140 - 6-7 arcsec.

To carry out an express analysis of data processing quality depending on the catalogue used we created

Table 2: Statistical results for the meteor images reduction based on the use of different catalogues. Images were obtained with the help of Schmidt telescope and astrocamera KO-140.

	Schmidt					KO-140				
Catalogue	N_m	σ_α	σ_δ	σ	N_s	N_m	σ_α	σ_δ	σ	N_s
SAO	29	1.34	1.20	1.70	588	196	3.93	3.42	4.82	6653
Tycho2	61	1.30	1.41	1.78	1192	10	3.49	2.64	4.23	471
USNO A2 Tycho-2	2102	1.58	1.58	2.01	66260	701	4.51	4.39	5.78	47071

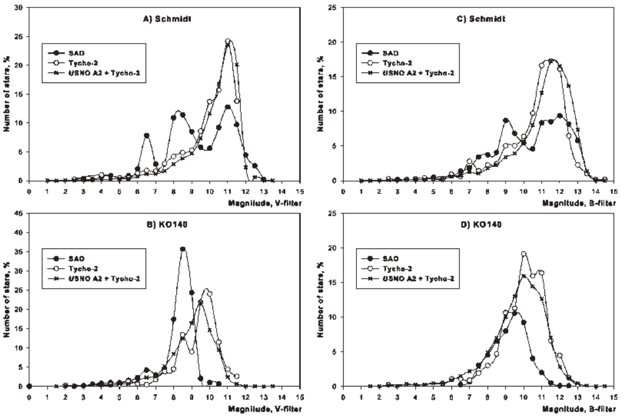

Figure 7: Percentage ratios of the stars in the reference catalogues with different magnitudes in V- and B-bands.

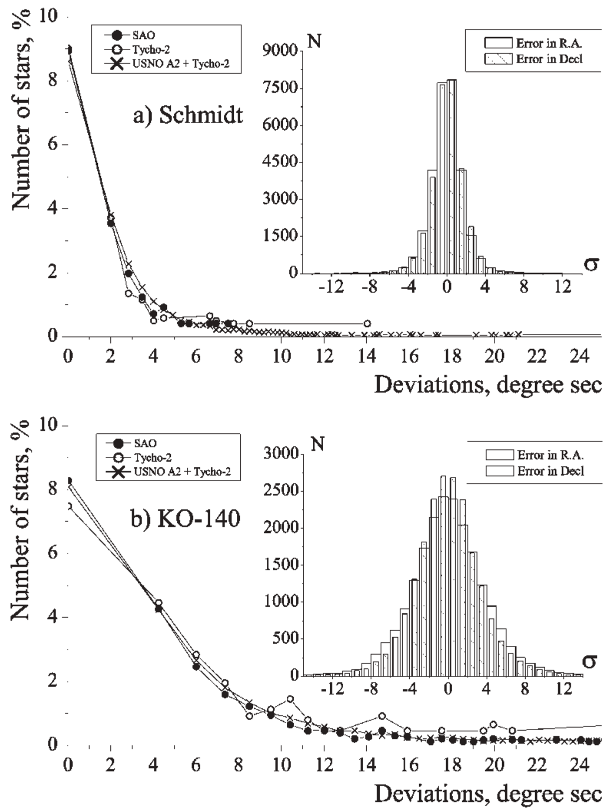

Figure 8: Percentage distribution of the stars from different catalogues depending on mean-square deviation.

software which enables one to get the following characteristics based on the measurements: the mean-square and maximum mean-square deviations (depending on the stellar magnitude), the distributions of the stellar magnitudes of the reference stars (V- and B-bands), the distributions of the mean-square deviations for the reference stars, the mean-square deviations mapped across the field of view. Summarizing, we note that selected catalogues are well appropriate for obtaining positional and photometric data which are necessary to reduce our observations. Both preliminary and subsequent analyses of all the catalogued data together with the results of our measurements allow one to correctly select the necessary catalogues depending on parameters of the telescope and astrocamera.

Fig.9 presents the distributions of the errors in position of the reference stars for Schmidt telescope and astrocamera equipped with KO-140 objective lens. Errors on α, δ and the total errors are presented separately. It is seen that the accuracy of the measurements is higher for the Schmidt telescope images. The ranges of the errors on α and δ are similar, and this indicates that there is no systematical error bias in our measurements. The large interval of the errors (up to 10 arcsec) is caused by that fact that during the meteor patrolling some cases can be met when the number of the reference stars within the field of view is limited (or the atmosphere transparency is bad, and this restricts the limiting magnitude; the same problem can also arise if observations are carried out during the twilight). An internal accuracy is determined by residuals found with reference stars, an external accuracy is found from residuals of the control stars. As the control stars we use that sample of stars that are not used to derive the parameters of the Turner equation. In addition, in order to determine an accuracy of our measurements we also use the precision which is conditioned by the residuals of the control stars just near to the meteor trajectory image.

After ***PSF*** creation we applied several tests to check the quality of the observational material reduction. As one of the tests we used IRIS code (Christian Buil, http: //www.astrosurf.com/buil, free access). Using this software and our ***PSF***, we obtained similar results (within the standard errors [2]). Another test is the positional observation of comets. As a result of the following comets observations: C/2002 T7 (LINEAR) and C/2006 W3 (Christensen), we sent their calculated equatorial coordinates to IAU Minor Planet Center. The results of the comet image reduction completely satisfied to the Minor Planet Cent requirement, and after that Kryzhanovka observational station was assigned the designation A85 Odessa Astronomical Observatory, Kryzhanovka, and the corresponding coordinated were published in Minor Planet Electronic Circular [3],[4].

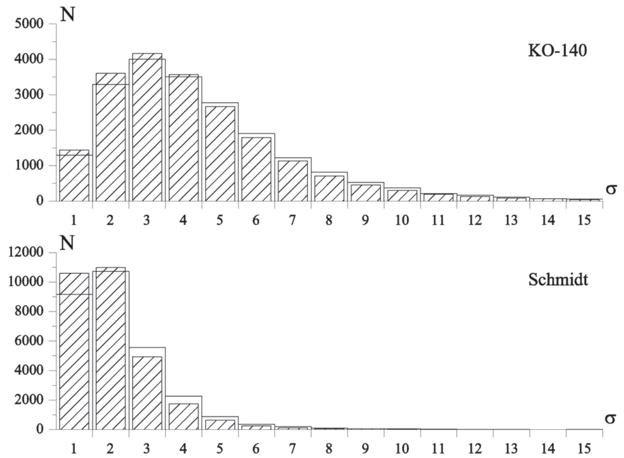

Figure 9: Distribution of the position errors for the reference and control stars.

4. Conclusions

Software ***PSF*** was created in the Department of the Solar system small bodies (Astronomical Observatory of I.I. Mechnikov Odessa National University). Using this software one can calculate equatorial coordinates of the celestial objects using the images of the reference stars obtained via TV method. This software was adapted for various optical systems and it was tested during the meteor and comet observations. For the star-like objects an error of the positional measurements is about 1.0-1.5 arcsec (for Schmidt telescope having focal length 50 cm). For the astrocameras equipped with Pentzval lens (focal length 14 cm) this error achieves 3-5 arcsec.

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