THE HIPPARCOS PHOTOMETRY AND VARIABILITY ANNEXES

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ABSTRACT

A summary of the photometric data obtained by the Hipparcos and Tycho missions is presented. The photometric signals and their reduction to magnitudes are described, as well as the passbands and their evolution. The main mission photometry provided on average 110 observations for each of the 118 000 stars observed during the mission. The accuracies for this epoch photometry range from a few millimagnitudes for the brightest stars to a few hundreds of a magnitude for the fainter ones. The data coverage was very much a function of ecliptic latitude, with the most homogeneous coverage near the ecliptic poles, and the most observations close to ecliptic latitude ±47°. The Hipparcos epoch photometry for all stars was investigated for variability and around 970 new periodic variables were discovered, as well as some 7000 unresolved variables (including micro variables, irregular variables, as well as variables for which a period could not be determined based on the Hipparcos data only). Median magnitudes as well as course variability indicators, derived from the epoch photometry, are included in the the main astrometric catalogue. All Hipparcos epoch photometry has been made available on the ASCII CD-ROM, disks 2 and 3. The Tycho epoch photometry was of lower accuracy, but provided useful colour index information. Only epoch photometry for a selection of the brighter stars in the Tycho catalogue has been preserved on the ASCII CD-ROM disk 4. More epoch photometry can be obtained through the CDS in Strasbourg. Mean magnitudes obtained from the Tycho photometry are, when available, included in the main Hipparcos astrometric catalogue.

Key words: space astrometry; photometry; variable stars.

1. INTRODUCTION

At an early stage in the preparations and development of the Hipparcos mission it was realized that the same signal that was used to obtain the astrometric results would also contain important photometric information. The Star Mapper signal as used in the attitude control for the main mission as well as for the Tycho mission could provide magnitudes in bands close to the Johnson B and V bands, while the main mission could provide a broadband magnitude with relatively high precision. Although in terms of passband definition the Hipparcos main mission photometry was not ideal, it was able to provide a set of photometric measurements that is unique in quantity, homogeneity and sky coverage. This large quantity of data could also be used for variability investigations of all stars observed and for verification of some properties of ground-based photometric observations. The Tycho photometric data was primarily used to provide much improved colour information for stars in the Hipparcos mission. Colour information was important in many reduction processes, and ground based observations were often inhomogeneous, inadequate or unavailable.

The analysis of the Hipparcos photometry took place in three stages:

- the reduction of the processed photon-counts to magnitudes by CERGA for the FAST consortium, and the RGO for the NDAC consortium, with system and standard star definitions done in Geneva;
- the merging and quality control of the reduced photometric data and the preparation of the epoch photometry files, done at the RGO;
- the variability analysis by Geneva Observatory and the Royal Greenwich Observatory, the preparation for the atlas of light curves (Geneva), and the naming of the new variable stars (Moscow).

The analysis of the Tycho photometric data was done by the TDAC consortium in Tübingen, with independent checks on a selection of the data by the RGO and a quality assessment at Geneva Observatory. All analysis and merging was supervised by the photometry working group, set up by the Hipparcos Science Team and led by Dafydd W. Evans. Table 1 lists the main people involved in the various tasks.

The present paper gives brief summaries of all the main aspects of the photometric analysis. More complete descriptions can be found in the Hipparcos and Tycho Catalogues, ESA (1997), Volumes 1, 3 and 4. Section 2 presents the photon count signals used as input for the photometric analysis, and a brief summary of their analysis to a measure of stellar intensity. The passbands belonging to these signals are also shown. Section 3 summarizes the main aspects

Table 1. Consortia members involved in the photometric analysis.

Name	Affiliation	Reduc.	Merg.	Variab.
D.W.Evans	NDAC	*	*	
L.Eyer	INCA			*
J.-L.Falin	FAST	*		
M.Grenon	INCA	*	*	*
V.Großmann	TDAC	*		
J.-L.Halwachs	TDAC	*		
F.van Leeuwen	NDAC	*	*	*
F.Mignard	FAST	*	*	
M.J.Penston	NDAC			*
M.A.C.Perryman	ESTEC			

of the reduction of the measured intensities to calibrated magnitudes, and the effect of the changes in the passband on these reductions. It also explains the implementation of the final passband definition and colour corrections. Section 4 describes the quality control after the main reductions, the final corrections that were applied to the reduced data and the merging into one photometric data base, the Hipparcos and Tycho Epoch Photometry Annexes. Section 5 presents the main statistical aspects of the Hipparcos epoch photometry, such as numbers of observations, accuracies, and data coverage. Section 6 presents some of the techniques used in the variability analysis and a summary of the overall results. Section 7 summarizes the different ways in which the photometric data are presented, and finally Section 8 gives a summary of results for comparisons with ground-based photometric data.

2. THE INPUT SIGNALS

The main mission astrometric data was obtained from the signal of a stellar image moving across a modulating grid, and being measured by an image dissector tube photon counting device. Only a small area of the grid, 30 arcsec diameter, was visible for the image dissector tube at any one time. It did, however, see two parts of the sky simultaneously. An example of the main mission signal is shown in Figure 1.

This signal was modelled using 5 parameters, representing the mean intensity, the amplitude and phase of the first harmonic and the amplitude and phase of the second harmonic of the modulation. The phase information was used for the astrometric analysis, the mean intensity and amplitudes of the harmonics for the photometric analysis. Main mission photometry derived from the mean intensity is referred to as dc-photometry, and is for fainter stars affected by the accuracy of background estimates. Main mission photometry derived from the modulation amplitudes is referred to as ac-photometry, and is in general about two times less accurate than the dc-photometry, not sensitive to background, but very sensitive to disturbances by other images.

The analysis of the signal used data collected over

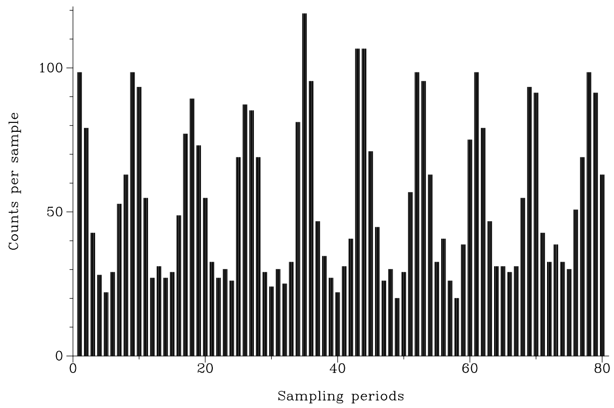

Figure 1. An example of a main mission signal for a 5th magnitude star. One sampling period equals $\frac{1}{1200}$ s.

a 32/15 s interval, within which between one and 10 stars were observed quasi-simultaneously. The amount of observing time spent per star depended on its brightness and on the competition for observing time from other stars. Accuracies on individual observations vary accordingly. In the reductions these intervals were referred to as frame transits. In the photometric reductions the data from these frame transits was used. It took around 9 frame transits for a star to cross the 0.9 degree field of view. In the final presentation of the data, only the combined, averaged data for a field of view crossing were preserved. They provided the epoch photometry data.

The Star Mapper signal was obtained from the passage of a star crossing four slits at unequal distances. Two such sets of slits were present, one set was vertical (perpendicular to the scan direction) and one set was inclined at an angle of 45 degrees. The light behind the slits was split into a B_T and V_T channel and measured with photomultipliers. Figure 2 shows an example of a star mapper signal in the B_T channel for a 6.6 mag star. This signal was modelled using calibrated single slit response functions, for which the position provided information on the transit time and the scaling the information on the signal intensity.

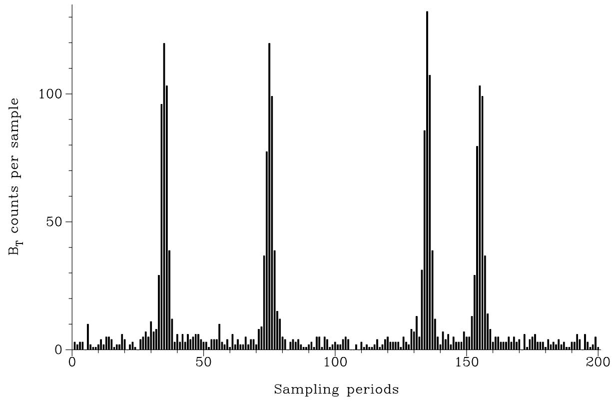

Figure 2. An example of a star mapper signal for a 6.6 mag star. One sampling period equals $\frac{1}{600}$ s.

Preliminary profiles for the Hp, V_T and B_T passbands were determined before the start of the mission. On the basis of these profiles a set of standard star magnitudes was established. During the mission, improvements were made to these determinations and much improved standard star selections and magnitudes were obtained and used. All main mission data were finally reduced to a passband which closely resembles the actual passband on 1 January 1992. Figure 3 shows the final passbands for Hp, B_T and V_T. A full specification of the passbands can be found in Volume 1 of ESA (1997), Table 1.3.1.

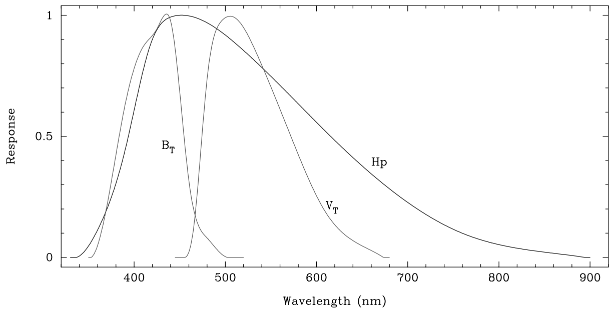

Figure 3. The Hipparcos and Tycho passbands.

3. THE DATA REDUCTIONS

The data reductions removed the positional and colour dependences from the measured intensities, using a set of around 20 000 calibration stars. This was done in different ways by the different reduction consortia. Calibrations were done in pseudo-intensity scale or an equivalent thereof, in order to avoid biases. In addition, in order to be able to use the mean intensities for the main mission signal, a background signal needed to be determined, in particular for the reduction of the fainter stars. An actual background was only measured in the Star Mapper signal, but was occasionally also available for the main mission when, due to attitude convergence problems, the main detector was not pointed at the intended stars. Using this information, together with a modelling of the galactic and zodiacal light, the background signal was predicted. A major complication in the background determinations was caused by the contribution of the radiation from outside the satellite, which varied strongly both intrinsically (the satellite operated around the time of a solar maximum) and due to the orbital position of the satellite (the VanAllen belts were encountered on average once every 5 hours). In order to preserve the possibility to check the influence of the background on the final magnitudes, all background values as implemented by the two reduction groups have been preserved in the photometry annex file.

Although colour coefficients were used in the data reductions, the entire colour dependence over the mission was recalibrated afterwards, using a calibration of the passband response for very red stars. This was made possible through a collaboration with the AAVSO, whose observers measured a selection of Hipparcos stars particularly for this purpose. Simultaneously some stars were measured with photometers at ESO, La Silla. These data made it possible to assign reliable colours and epoch photometry to Hipparcos measurements of several Mira stars and other long period red variables. In the standard reductions the extreme red stars could not be used due to their variability and the low number of stars available. A final recalibration of the colour coefficients for the FAST and the NDAC reductions was carried out by M. Grenon. The evolution of the colour coefficients as shown in Figure 4 represents the changes in the passband (it should be noted here that there were small differences between the passbands for the two fields of view and for the dc and ac components). One effect of these changes is that for stars that were reduced using the wrong colour a drift occurs in the final data. Such drifts can be corrected for afterwards, when better colours are available. A similar problem can exist for variable stars with large colour variations. These colour variations could not be accounted for in the data reductions, but can be corrected for afterwards if required.

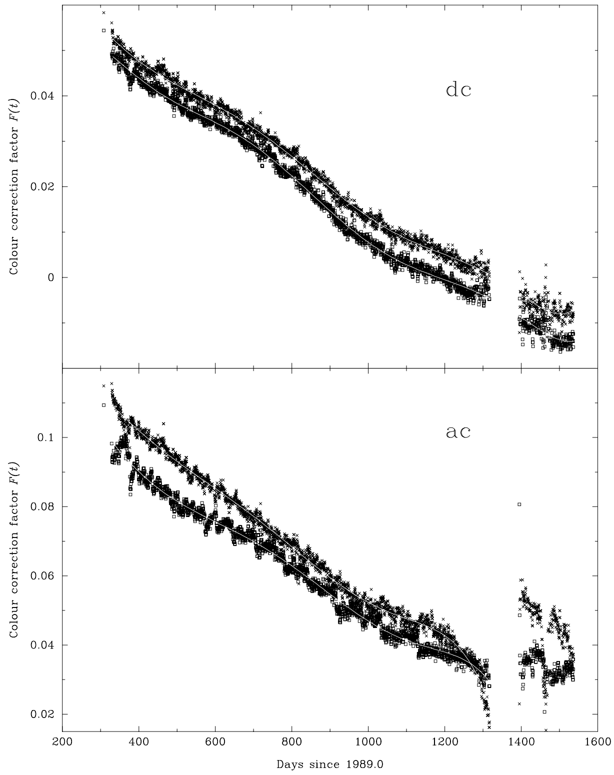

Figure 4. The evolution of the colour coefficients in the main mission photometric reduction, representing the changes that took place in the Hp passband. The two curves in each graph represent the two fields of view. Top: the dc-photometry derived from the mean intensities, bottom: the ac-photometry derived from the modulation amplitudes. Note the small difference between the passbands for the two fields of view and between the dc and ac components.

4. THE FINAL CHECKS AND DATA MERGING

Several checks were made on the final reduction results as obtained from FAST and NDAC. Remaining positional dependences of the photometric results were removed, as well as some as yet unexplained discrete small changes in the overall detector response. Furthermore, the error estimates on the epoch photometry were adjusted. These estimates were, due to the small number of observations used in determining an average, affected by a Student's-t distribution. Correlations between the two data sets were investigated too. These correlations exist between the residuals of individual measurements for constant stars for the reduction results as obtained in the two consortia. There are two contributors to these residuals: the error introduced by the original photon counts, and the error introduced by minor inadequacies of the data reduction methods used. The first type of error will be correlated between the two sets of results, while the second error will be largely uncorrelated. When the correlation between the FAST and the NDAC residuals is high, the influence of data reduction introduced errors can be considered small. Figure 5 shows the correlation coefficients as a function of magnitude, indicating some calibration problems for very faint stars (resulting from the background modelling) and for the brightest stars (response modelling).

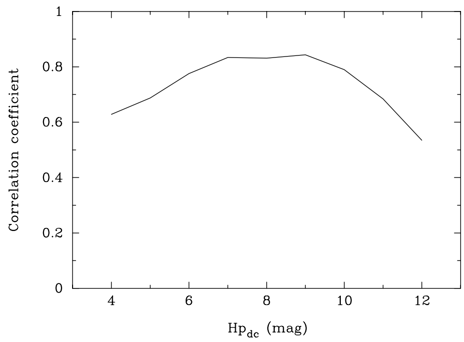

Figure 5. The correlation coefficient between the FAST and NDAC reduction results as a function of magnitude.

The Tycho data for the fainter stars required corrections for a bias in the magnitudes that resulted from the recognition process. A process, called decensoring, was developed to correct this bias on the basis of the unrecognized transits. This process is described in Chapter 9 of Volume 4 of ESA (1997).

5. STATISTICS

The statistical aspects of the Hipparcos and Tycho data are dominated by the magnitudes of the stars and by the way the satellite scanned the sky, using a predefined scanning law described in ecliptic coordinates. The relations between accuracies and magnitudes is shown in Table 2. The numbers of observations and some parameters describing the distribution of those observations over the 3.5 years of the mission are shown in Figures 6, 7 and 8.

Table 2. Standard errors on transit and median magnitudes.

mag	<Transit error>		<Error on median>			
	$Hp_{\rm dc}$	$Hp_{\rm ac}$	$Hp_{\rm dc}$	$Hp_{\rm ac}$	B_T	V_T
3	0.003	0.005	0.0004	0.0006		
5	0.005	0.009	0.0006	0.0010	0.003	0.003
7	0.008	0.019	0.0009	0.0019	0.008	0.007
9	0.015	0.037	0.0019	0.0039	0.026	0.022
11	0.033	0.072	0.0044	0.0079	0.12	0.12

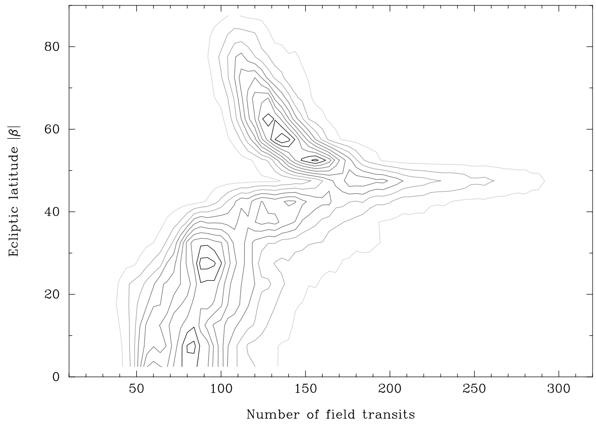

Figure 6. The total number of observations per star as a function of ecliptic latitude. The first contour represents 10 stars, every next contour adds 20 stars. The highest contours represent around 200 stars.

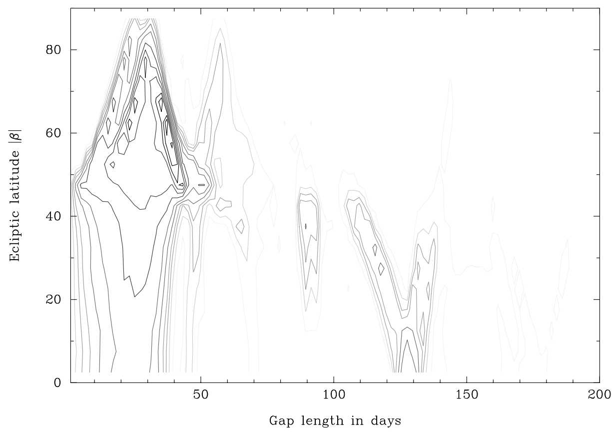

Figure 7. Distribution of the lengths of gaps as a function of ecliptic latitude. Gaps longer than 1.5 days were counted for all stars. The lowest contour represents 200 gaps observed, increasing by 400 until 1400, then by 600 until 2600, and then by 900 until 8900. The majority of gaps is between 10 and 40 days.

6. VARIABILITY INVESTIGATIONS

All main mission photometric data was investigated for variability by first examining the χ^2 statistics of

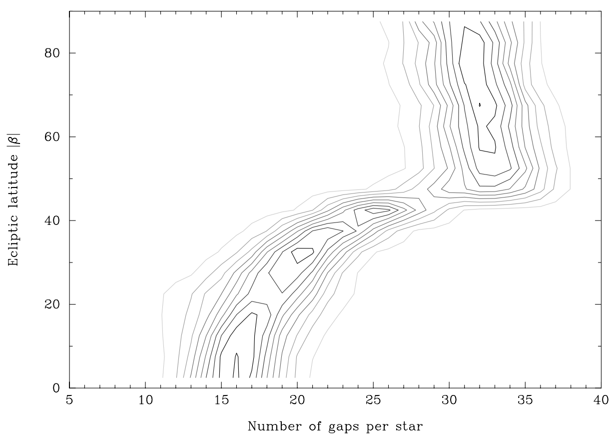

Figure 8. Distribution of the number of gaps as a function of ecliptic latitude. Gaps longer than 1.5 days were counted for all stars. The contours represent the relative distribution of the gaps, with the lowest contour at 1 per cent, and every next contour 2 per cent higher.

the weighted residuals. The χ^2 value was translated in a probability of occurrence. In case no stars were variable, this probability would be proportional to the number of stars observed at a given probability. The logarithm of the probabilities were accumulated in bins. Figure 9 shows the observed distribution, and, as a dashed line, the expected distribution for constant stars. The excess to the right of this line is due to variability. However, on an individual basis only stars very much to the right of this line (with $\log(prob) < -8$) could be further investigated for periodicity. This amounted to some 12 000 stars.

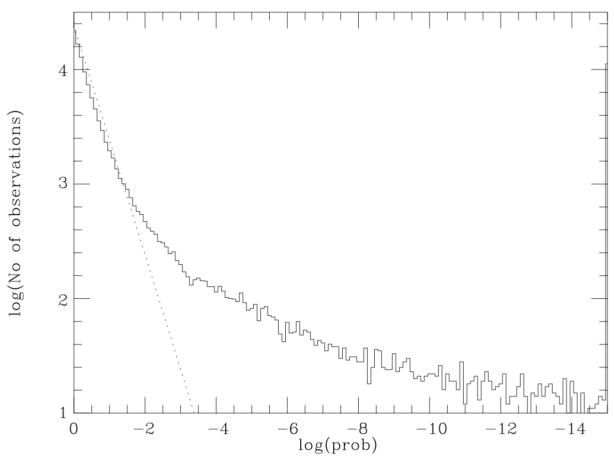

Figure 9. The observed distribution of χ^2 values (full line) compared with the distribution for all stars being constant (dotted line). The right-most bin contains all values at or below -15.

The methods used at the RGO were described by van Leeuwen et al. (1997). The choice of methods was the result of a search through the literature for those methods best capable of coping with the rather poor data coverage. Two methods were used in parallel, the discrete fourier analysis as described by Scargle (1982) and Scargle (1989) and the analysis of variance as described by Schwarzenberg-Czerny (1989). In addition to this, a method of curve fitting using cubic splines (except for Algol-type eclipsing binaries, for which linear splines were used) and period fine tuning was developed. This also provided minimum and maximum luminosities, zeropoints and accuracies on the period estimates (see van Leeuwen et al. 1997). The period searches were in addition supported by a data base of references for photometric or other observations of stars contained in the Hipparcos Input Catalogue.

The methods used in Geneva are described by Eyer (1997). A wider variety of tests was used for the detection of variability, using not only a χ^2 but also, amongst others, asymmetry of the residuals, checks for outliers and trends. This made it possible to detect a wide range of variability types as well as trends. Any trends detected were checked against the colour index used in the data reductions. As was explained in Section 3, errors in the colour index would cause trends as a result of the changes that took place in the passband response. A search for outliers was made, in order to exclude cases where the variability indicator was raised only as a result of one or two data points (which could be real but did not offer the possibility for further investigations). Three methods were used for period searches:

- Fourier analysis for small amplitude variables (Deeming 1975 and Ferraz-Mello 1981);
- Stellingwerf's method for large amplitude variables (Stellingwerf 1978);
- Renson's method for eclipsing binaries (Lafler & Kinman 1965, Renson 1980).

The light curves were fitted with a weighted linear regression based on a Fourier series. This ensured continuous properties of the solutions in the phase diagram. The number of harmonics was chosen automatically from criteria depending on the period, asymmetry, amplitude and noise level of the light curve. Every light curve was checked and numbers of harmonics were adjusted when necessary. This fit provided the final period, minimum and maximum light and the reference epoch. Figure 10 shows schematically the methods used in Geneva.

The variability results as obtained in Geneva and at the RGO were regularly compared and in most cases agreement was reached. In few cases where this was not the case or where periods were altogether uncertain, notes were added to the variability annexes. All references are also included in the printed catalogue and on the ASCII CD-ROM. A summary of the detections is presented in Table 3.

7. PRESENTATION OF THE DATA

The photometric data is made available in three forms: the epoch photometry in the Hipparcos and Tycho Epoch Photometry Annexes; in the form of of tables and graphs for the results of the variability investigations; and in the form of median values

Table 3. Summary of the variable stars investigations.

Number of entries variable or possibly variable	11597	(8237 new)
Periodic Variables	2712	(970 new)
Cepheids	273	(2 new)
δ Scu & SX Phe	186	(9 new)
Eclipsing binaries	98	(36 new)
Other types	1238	(576 new)
Non-periodic and unresolved	5542	(4145 new)
Not investigated	3343	(3122 new)

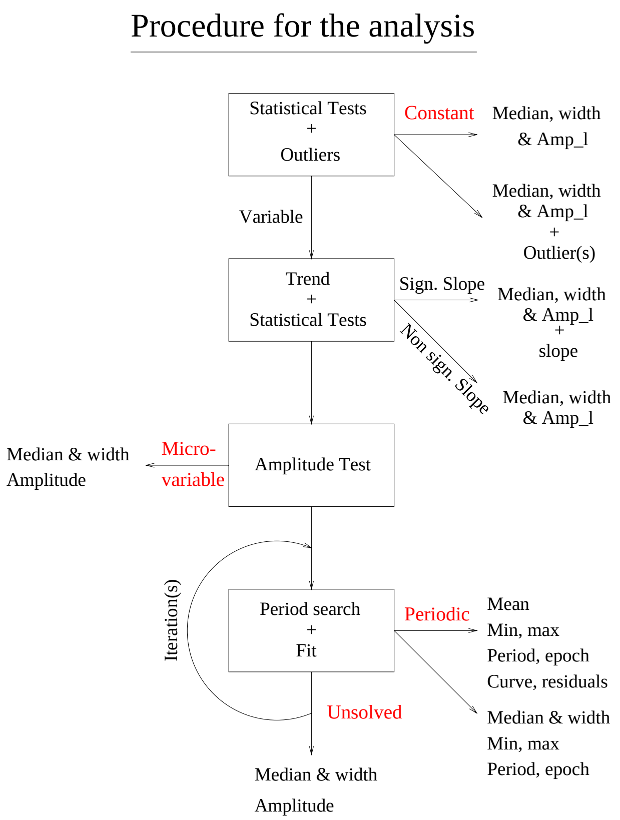

Figure 10. Schematic representation of the variability analysis methods used in Geneva.

in the main catalogue, supplemented in some cases by ground-based information on star colours. The epoch photometry contains information on the background level applied, a flag indicating any problems that were considered may exist, and the position of the other field of view with a pointer to a file giving possibly disturbing objects noted at that position.

8. COMPARISONS WITH GROUND–BASED DATA

The global nature of the Hipparcos and Tycho photometry and the accuracy of in particular the Hipparcos photometry as well as the large number of measurements make this set of photometric data an almost ideal reference data base for ground-based photometric systems. Such comparisons were done for the Walraven system, the Geneva system and the Johnson UBV system. Only for the Geneva system there were found systematic errors as a function of right ascension. These comparisons are described in Chapter 21 of Volume 3 of ESA (1997).

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Many people contributed to the analysis of the variable stars. In addition to those mentioned in Table 1 I would like to thank I. Zegelaar and J. Lub (RR Lyraes), C. Waelkens (low amplitude red variables), S. Meara (literature searches), M.B. van Leeuwen Toczko (statistics of variability analysis), and I. Howard (librarian at RGO). The observations provided by the AAVSO were of crucial importance for the proper calibration of the very red stars. The Sternberg Institute in Moscow provided at very short notice names to some 3000 newly discovered variable stars.

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