Problems encountered in the Hipparcos variable stars analysis

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Abstract. Among the 17 volumes of results from the Hipparcos space mission, two are dedicated to variable stars. These two volumes arose from the work of two groups, one at the Geneva Observatory and one at RGO (Royal Greenwich Observatory), on the 13 million photometric measurements produced by the satellite for 118,204 stars.

The analysis of photometric time series permitted us to identify several instrumental and mathematical problems: overestimation of the precision, offsets in the zero-points depending on the field of view, mispointing effects, image superpositions, trends in the magnitudes, binarity effects (spurious periods and amplitudes) and time-sampling effects. In this article we summarize some of the problems encountered by the Geneva group.

1. Introduction

The variable star analysis of the Hipparcos photometric data was an iterative process in interaction with the FAST and NDAC data reduction consortia. We started with data extracts from FAST, then from NDAC and finally worked on the whole merged data set, that is on the 118,204 time series.

The result of variable star analysis is a beautiful by-product of the mission and it was clear that it had to be published at the same time as the astrometric results (ESA 1997). The time available for the photometric analysis was then short in order to match the deadlines. The teams were put under strong pressure. The approach was then to produce a robust analysis restricting the analysis to statistically well-confirmed variables, leaving suspected variables and ambiguous cases for further analysis.

Because several instrumental problems were identified and solved, the variable star study definitely improved the overall quality of the Hipparcos photometry available now on the CD-ROMs.
Figure 1. HIP 96647. Left: magnitudes before the data merging, open squares are for the following FOV, crosses for the preceding FOV. Right: the corrected final solution.

2. Hipparcos main-mission photometry

Although the telescope diameter is small (29 cm), Hipparcos achieved a high photometric precision in the wide $Hp$ band (335 to 895 nm), thanks to the chosen time allocation strategy and to the frequent on-orbit photometric calibrations, making use of a large set of standard stars. The time allocated for a star observation was adapted to its magnitude in order to homogenize the astrometric precision. The photometric reduction was made in time slices of 10 hours, called reduced great circles (RGC). During that time interval, the satellite scanned a closed strip in the sky, measuring about 2600 stars, among them 600 standard stars.

The FAST and NDAC consortia independently reduced the photometry. They had to map the time evolution of the spatial and chromatic response of the detection chains for both fields of view (FOV), the preceding and the following. In Fig. 1, a zero-point problem between FOV magnitude scales is shown, before and after its correction.

The light of the star was modulated by a grid for astrometric purposes. The transmitted signal was modeled by a Fourier series of 5 parameters. From this model two estimates of the intensity were done: one, measuring the integrated signal, the “DC mode”, was robust to the duplicity but more dependent on the background, and the second, measuring the amplitude of the modulation, the “AC mode”, was sensitive to the duplicity but not to the background (cf. van Leeuwen et al. 1997). These two estimates and their accuracies are given in the Epoch Photometry Annex (CD-ROM 2) and in the Epoch Photometry Annex Extension (CD-ROM 3).
3. Noise and magnitude

The precision of the magnitude is a function of the magnitude itself. In addition, for a star of constant magnitude, the errors may be variable. The data are then heteroscedastic. The correlation between the error and the magnitude, may generate some problems. For instance, the weighted mean cannot be used to estimate the central value of the magnitude distribution, if the amplitude is large as for the Miras. The global loss of precision as the satellite ages (Eyer & Grenon 2000) also needs to be considered. The usual period search algorithms are also sensitive to the inhomogeneity of the data.

3.1. Quoted transit errors

During a single transit, a star was measured 9 times on average, the transit error $\sigma_{Hp}$ was derived in a first approximation from the spread of these measurements. However, the estimation did not include offsets which might have affected a whole transit, e.g., due to a mispointing or to a superposition of a star from the other FOV. In our first analysis, an empirical law was determined to correct the transit error underestimation, otherwise the number of candidate variable stars did not appear credible.

During the phase of data merging, ad-hoc corrections were computed (Evans 1995). The errors were studied with different methods, comparing first the “average” error estimated from the $\sigma_{Hp}$ with the dispersion of the measurements on $Hp$. Another study by Eyer & Genton (1999) was made on the quoted errors using variograms; it showed a good general agreement with the Evans results, with some mild underestimations for faint magnitudes and some mild overestimations for the bright magnitudes in Evans’ approach.

3.2. Time sampling

The time sampling was determined by the satellite rotation speed and by the scanning law which were optimized to reach the most uniform astrometric precision over the whole celestial sphere. The total number of transits per star is a function mainly of the ecliptic latitude. The time intervals between successive transits are 20-108-20-etc. . . minutes. The transits form groups which are separated by about one month, but the number of consecutive measurements as well as the time separation between groups of transits can vary strongly from one star to another.

3.3. Chromatic aging

The irradiation by cosmic particles reduced the optical transmission with time. This aging was chromatic; it was worse than expected because the satellite had to cross the two van Allen Belts twice per orbit. Furthermore, the satellite was operational during a maximum of solar activity. For instance, the magnitude loss over 3.3 years was 0.8 mag for the bluest stars and only 0.15 mag for the reddest.

The aging of the image dissector tubes were not uniform and distinct for both FOVs, therefore the aging corrections had to be calibrated as functions of the star location on the grid for each FOV.
Magnitude trends: An odd effect of the chromatic aging was the production of magnitude trends in the $H_p$ time series. As the transmission loss was colour dependent, the magnitude correction had to be a function of the star colour. A colour index, monotonically growing with the effective wavelength of $H_p$ band, had to be evaluated from heterogeneous sources. The precision of the equivalent $V - I$ was highly variable. For stars with “bad” $V - I$ colour, the magnitude correction was erroneous and produced a trend. A colour bluer than true generates a spurious increase of the luminosity with the time. An example of a trend is given in Fig. 2.

Selection of trends: Stars like Be stars may also show quasi-linear trends over the mission duration. The identification of spurious trends was iterative. LPVs, showing Gaussian residuals when modeled with a trend on top of their semi-periodic light-curve, were sorted first. But there was much more diversity in the data showing trends, true or spurious. So we used an Abbe test (Eyer & Grenon 2000) for a global detection. Stars with an Abbe test close to 1, or with a large trend or with very long periods, were flagged. Stars with possible envelopes were not retained. After visual inspection of the time series by Grenon, the number of stars selected by these different procedures was 2412.

Correction of the star colour: The amplitude of the magnitude drift was used to correct the star colour. Indeed, if a time series shows a trend $\alpha$ which may be imputed to an incorrect initial colour, there is a possibility to recover the true star colour by the relation:

$$(V - I)_{\text{new}} = (V - I)_{\text{old}} - 14290 \alpha$$

where $\alpha$ is expressed in magnitude per day.
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Figure 3. Two examples of series with outlying values. Left: HIP 35527 the case of a light pollution from the other FOV, where Sirius is the perturbing star (this case is not flagged); Right: HIP 57437 an example of mispointing effect with low values correctly flagged (open circles).

Every selected case was investigated to decide whether the trend could be a consequence of an incorrect colour; 965 $V - I$ indices were corrected this way with certainty and the origin of the errors on the colours was traced back.

4. Outlying values

When studying variable stars, outlying values and anomalous data distributions are of great interest. Namely, it is important to distinguish outliers of instrumental origin from those due to stellar physical phenomena. Some stars show luminosity changes on very short time scales. For Algol eclipsing binaries, the duration of the eclipse is short with respect to their period. With non-continuous time sampling, eclipses may appear as low luminosity points. UV Ceti stars show strong bursts in the U band on very short time scales. However, because of the width of the $Hp$ band, the photospheric flux in the redder part of the band largely dominates that of the burst, with the result that no burst was detected with certainty in the M dwarfs.

In Fig. 3 we present two cases of outlying values of instrumental origin.

4.1. Instrumental outliers: Mispointing effect

The pointing precision of the satellite was normally better than 1 arcsec. However after Earth or Moon eclipses and especially near the end of the mission when most gyroscopes were faulty, the problems of mispointing were more acute. The radius of the photocathode was 15 arcsec, with a lower sensitivity towards the
edge. An inaccurate pointing was inducing a loss of counted photons, leading to
dimmer points in the time series.

The problems with extended objects were even worse, depending on their
sizes. A similar situation happened with visual double systems when the sepa-
ration was around 10 arcsec. In this case the target was either the primary or
the photocenter of the system. From time to time the companion was on the
edge or out of the FOV, diminishing the amount of collected light. Even when
the two components were measured alternatively, the not-measured star might
have sometimes entered in the FOV producing a luminosity excess mimicking a
burst.

4.2. Instrumental outliers: Light pollution

A neighbour star could contaminate the observed star, although most of the
identified cases were rejected during the Input Catalogue compilation. The
perturbing star was possibly a real neighbour or, more often, a star belonging
to the other FOV. Several configurations are possible:

- A star from the other FOV was added to the measured star. That is
called a superposition effect. Stars in the Galactic plane were more often
perturbed because of the higher star density.

- The perturbing star was very bright and caused scattered light in the
detection chain. This veiling glare could be felt even if the disturbing star
was further than 15 arcsec.

- When the separation was greater than 15 arcsec, the two effects of pollution
and mispointing could produce high values of fluxes of the dim component.

Fig. 4 shows the correlation between the asymmetry of the time series for
double systems and the angular separation $\rho$. The asymmetry is positive for
dimmer outlying values, and negative for pollution by the primary (bright out-
lying values).

4.3. Selection of outliers

The problems caused by the outliers were very acute at the beginning of the
analysis; we had then to take drastic measures before searching for periods and
amplitudes. We removed:

- all measurements with a non-null flag.

- the end of the mission, if the dispersion of the data was smaller than 0.3
  before the day 8883. (the data for large amplitude variables were kept up
to the end of the mission).

- high luminosity values if there was a magnitude jump in consecutive tran-
sits.

- bad-quality measurements with transit errors higher than $\epsilon(\Delta C) = 0.0005 *$
  $10^{0.167 H_{DC} + 0.0014}$. 
Figure 4. Light pollution and mispointing effects for double stars as a function of the angular separation $\rho$.

- temporarily one or two outliers to check their impact on the result of an analysis based on truncated time series.

This removal represents a reduction by 6% of the number of measurements with non-zero flag.

Suspect transits from the analysis of outliers were transmitted to the reduction consortia, who flagged them according to the origin of the disturbance.

5. **Alias and spurious periods**

The spectral window produces spurious periods when it is convoluted with the true spectrum. As a result, spurious periods around 0.09 d were frequently found for long periods or irregular variables as well as for stars showing magnitude trends. Periods of about 5 d for SR variables turned out to be nearly all spurious. With the Hipparcos time sampling the spectral window changes from one star to another and the alias effect had to be studied on a per star basis.

A 58 day periodicity was found in many time series when applying the period search algorithm. This period corresponds to the time interval between consecutive measurements of double systems under the same angle with respect to the modulating grid (the modulated signal is higher when the components are parallel to the grid).
6. Advice about the use of the data

We want to stress that caution should be taken in handling the epoch photometry, especially when the signal to noise ratio or when the number of retained measurements are small. The effects of multiperiodicity are generally very tricky. The spectral window should be investigated in detail and periods near sampling frequencies should be taken with care, in particular in the range 5 to 20 d where the Hipparcos photometry has the weakest detection capability. 

The selection of photometric data can be made according to their flags, the estimates of the transit errors and the background intensities. In case of doubt about outlying data, a look to the magnitude difference $AC - DC$ will reveal problems related to duplicity and image superpositions since the amplitude of the modulated signal is reduced in the case of misaligned sources with respect to the grid orientation. The contents of the opposite FOV can be investigated thanks to their published positions. It is suggested to correct rather than to eliminate data since a loss of information might twist statistics. For an example of a successful selection procedure applied to the data of HIP 115510, see Lampens et al. (1999).

7. Conclusion

Performing accuracy photometry in space is not free from problems. The same is true for the data analysis. Once the origin of the encountered problems is identified, it is possible to cope with them and determine precisely the domains of validity of the algorithms for search of periods and amplitudes. Globally the ratio quantity-quality generated by this mission for the study of variability has no equivalent up to now.

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