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Comparison of the first results from the Hipparcos star mappers* with the Hipparcos Input Catalogue

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Abstract. Preliminary positions and magnitudes derived from the analysis of 12 weeks of observations from the Hipparcos star mappers are systematically compared with the various sources of ground-based data used in the Hipparcos Input Catalogue. These comparisons allow to cross-check the accuracies claimed by the various sources of ground-based data and by the analysis method of star mapper data. The parameters obtained for double stars, relative position and orientation, are also compared with ground-based data.

Key words: Hipparcos – catalogues – astrometry – reference frames – photometry – double stars

1. Introduction

The transits of Hipparcos programme stars through the satellite star mappers are recorded by the two photometers of the Tycho experiment (Høg et al. 1991). The knowledge of the attitude of the satellite at the epochs of the star transits, added to the determination of the transit times with respect to the star mapper grid, allows us to obtain corrections to the assumed positions of the observed stars on the sky. In addition, the photon counts, calibrated by the observation of photoelectric standard stars, allow the determination of B_T and V_T magnitudes. B_T and V_T stand for magnitudes in the Tycho bands (Grenon 1988). The profiles of these bands are close to the B and V of the Johnson system, with some discrepancies for the reddest stars. The process is limited to stars brighter than $V_T = 10$ approximately.

The analysis of these data have been performed for about 47 000 stars of the 118 000 of the Hipparcos Input Catalogue as part of the data reduction work performed at the Royal Greenwich Observatory (RGO) within the frame of the Hipparcos Northern Data Analysis Consortium (NDAC). Although still far from reaching the performances ultimately expected from a full analysis of the complete Hipparcos data set, these preliminary data already match the quality of most ground-based data. A total of 1.2 million transits were used. The positions and magnitudes obtained from these data (hereafter called the 'RGO catalogue') are compared with the data collected by the Hipparcos INCA Consortium which was responsible for the construction of the observing programme for Hipparcos (Turon et al. 1991). Extensive compilations and new observation programmes were undertaken by this Consortium to fulfil the ESA requirements about positions at epoch 1990 and magnitudes of programme stars (Jahreiß et al. 1991, Grenon et al. 1991). For each programme star, the best data for positions, proper motions, magnitudes and colours available within the 'INCA Database' were retained. The comparison of these data with the first results obtained from the Hipparcos star mappers allow a reciprocal check of both sets of data.

2. Data obtained from the Hipparcos star mappers

2.1. Positions

The star mapper data stream as received in RGO consists of stretches of 250 sampling periods around the predicted transit times of stars from the Input Catalogue. The star mapper photon count records are reduced to transit times and intensities, which in combination with the assumed positions of the stars involved provide information on the orientation of the satellite axes. Transits from the two fields of view and through the inclined and vertical slit groups describe in this way the evolution of the payload frame of reference, providing the reconstructed attitude. In NDAC the satellite attitude is determined relative to a dynamical model, strengthened by means of gyro readings (see van Leeuwen et al. 1991, Paper I). This allows the amount of information that has to be extracted from only the star mapper transits to be minimal, thus leaving information on the individual positions of the stars involved almost undisturbed in the form of transit time residuals.

The transit time residuals are collected as described in Paper I. In the reduction of the data from the satellite already distributed some 1.2 million transit time residuals from 12 weeks of data spread over 1.2 years were collected. 51 000 stars each had between 8 and 200 independent observations, which were used to improve the positions and magnitudes of these stars (47 000 stars from the Input Catalogue and 4 000 additional stars used for the 'Initial Star Pattern Recognition', i.e. for the initial attitude acquisition). The positional system defined by these updated positions is a combination of the original

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* Based on observations made with the ESA Hipparcos satellite, and on work performed within the INCA and NDAC Consortia.

Input Catalogue and the smoothing effect of the attitude reconstruction process. In the attitude reconstruction two strips of sky with a length of 12–18°and separated by the basic angle of 58°, are used to determine the attitude of the satellite over one jet-firing interval. Transits through the vertical slits in both fields of view determine the 'spin-phase'. Transits through the inclined slits determine the spin-axis position. If systematic errors are present in either or both of these strips, then, in the case of the transits through the vertical slits, the **differences** between these errors will enter the residual transit times, and will get removed from the catalogue. In the inclined slits the attitude will model the systematic errors, and only remove the individual errors.

About half the sky was covered by scans in different directions and thus the attitude reconstruction combined the data in these areas with various other areas on the sky. One third of the sky was covered by only one scan direction. The updating process was repeated several times over all 12 weeks of data, using the previous updates as starting points. The internal consistency figures clearly showed a system slowly converging. This way, some of the smaller scale systematic errors were automatically removed from the Input Catalogue. Larger scale systematic errors cannot be removed easily in this process, but were in general reduced (see also Lindegren et al. 1991).

2.2. Double stars

As was described in Paper I, double stars received a special treatment in the star mapper processing. The main reason to reduce the double star transits through the star mapper are to provide the processing of image dissector tube double star data with starting points on separation and orientation. In addition, it was necessary to provide better absolute positions for double stars than there were available from ground-based measurements. In the star mapper processing, the aim is to process double stars with separations above 1.5 arcsec in much the same way as single stars once they have had their positions updated. A properly resolved and recognized double star is unlikely to disturb the attitude reconstruction in the way an unresolved double can do it.

The accuracy of the relative position and orientation is, as always in differential measurements, higher than the absolute positions. The transit time differences are not affected by errors in the attitude reconstruction, and reflect directly the separation on the sky along the direction of the scan (and at an angle of 45°to the scan for transits through the inclined slits). The accuracy of the transit time differences is thus set by the accuracy of the transit time determinations. The rms accuracy for single transits under 'apogee-conditions' (low background signal), which is an indication of the best transit time accuracies available, ranges from 5 milli-arcsec at 5 mag to 40–60 milli-arcsec at 8-10 mag.

2.3. Photometry

The reduction of the star mapper data provides intensities in the B_T and V_T channels. These intensities have been calibrated to one system, removing effects of positional and colour dependence. They are collected (as described in Paper I) as intensities in the catalogue, with a simple relation to magnitudes. This avoids the creation of biases that would occur if magnitudes were collected in the catalogue. The calibration of the magnitudes was in an experimental phase during the processing of the provisional data, and it is therefore not surprising that some minor effects are still left in the data. The current comparison exercise is one of the tools helping us to recognize and remove these last discrepancies before the bulk processing of the data starts.

3. Data included in the Hipparcos Input Catalogue

Due to the detection system of the Hipparcos satellite and to its operational mode, the positions and magnitudes of the programme stars had to be known in advance with some accuracy. The specifications of ESA were ±1.5 arcsec on the 1990 positions and ±0.5 mag on the B or V magnitude for all programme stars, and a somewhat better accuracy on positions for a subset of stars used for real-time satellite attitude determination. As the stars were submitted for observation with Hipparcos on the grounds of scientific proposals, not taking into account the availability of accurate positions or magnitudes, extensive programmes of compilation and new observations or measurements were undertaken by the INCA Consortium (Turon et al. 1991).

3.1. Astrometric data

Astrometric data for 25 000 stars did not match the required accuracy (Jahreiß et al. 1991). New observations with Automatic Meridian Circles (10 000 stars observed at Bordeaux and La Palma) and plate measurements (100 000 stars measured on the ESO Sky Survey or CPC2 plates) were undertaken. For plate measurements, it was, indeed, decided to remeasure all candidate stars present on each plate. This yielded to a considerable overlap with earlier results, and allowed the detection of possible errors (mostly errors in star identification) not only in the plate measurements themselves but also in earlier measurements.

In parallel, the contents and precision of the available astrometric catalogues were investigated and a hierarchy established. Moreover, when possible, all available positions and proper motions were reduced to FK5. Finally, when all newly obtained data were available, the best positions and proper motions were selected to be retained in the final version of the Hipparcos Input Catalogue.

At the end of this extensive work, it was concluded that the final positional accuracy of the Hipparcos programme stars for epoch 1990 is better than 0.5 arcsec in the northern hemisphere, and better than 0.7 arcsec in the southern hemisphere, and that no systematic trend with respect to the FK5 system is present if the whole catalogue is considered. A complete description of the astrometric data included in the Hipparcos Input Catalogue can be found in Réquième (1989), Jahreiß (1989) and Jahreiß et al. (1991); references of all catalogues used can be found in Jahreiß (1989).

3.2. Photometric data

The specifications of ESA were only requiring 'one approximate magnitude, B or V, to within ±0.5 mag'. It rapidly appeared that, for reaching the accuracy expected on the astrometric parameters, an adequate observing time should be allocated to each programme star, as a function of its magnitude in the

Hipparcos band (H_p). As a result, it was realized that the an accuracy of $\pm 0\overset{m}{.}5$ mag on the Hipparcos magnitude itself was desirable. This band has an effective wavelength close to that of the V band of the Johnson system, but much wider, and the differences $H_p - V$ are significant for very red or very blue stars (Grenon 1988). Thus, one magnitude (B or V) **and** a colour had to be obtained for all programme stars.

The photometric data available for the 214 000 proposed stars at the start of the Input Catalogue work, coming from the SIMBAD database or from the proposers, was very heterogeneous: accurate photoelectric photometry was available for about 26 000 stars, acceptable B and V magnitudes were obtained for about 145 000 stars from photographic photometry or estimates of blue and visual magnitudes, but about 17 000 stars had only incomplete or unreliable photometric information. Extensive observation programmes were performed in various photoelectric systems, and new observations were obtained for about 7 700 stars in 3 to 7 bands (Grenon 1991); at the end of the Input Catalogue work, as a result of new observations and extensive compilations, B and V photoelectric photometry was available for about 46 000 stars and V photoelectric photometry coming from the Carlsberg Automatic Meridian Circle (CAMC) was available for about 13 000 stars. All these new data were used to obtain the data required for the mission: H_p, B_T and V_T.

In addition to this observational work, a new extinction model was derived to improve the determination of the reddened Johnson and Tycho colours obtained from the available MK or HD spectral types when only one magnitude was considered as reliable (Arenou et al. 1991). Colours were obtained in this way for about 60 000 single stars of the Input Catalogue.

3.3. Data on double and multiple stars

The situation was still worse for double and multiple stars, and a considerable effort was devoted first to make the available data easy to handle and avoid component mis-identification, and then to complement these data by new observations or measurements of positions or magnitudes where necessary (Dommanget 1989, Jahreiß et al. 1991). As for single stars, the knowledge of positions and magnitudes was required for each system, or for each observable component, but, in addition, the knowledge of the geometry of the systems and the relative magnitudes of the components was highly desirable to correct for the possible perturbing effect(s) caused by the presence of additional component(s) not taken into account for direct observation (Turon et al. 1989).

4. Comparison of the astrometric data

4.1. Global comparison

The differences between the data of the Hipparcos Input Catalogue and those obtained from star mappers are illustrated in Fig. 1, considering the 47 000 stars for which data are available from the analysis of the star mapper signals, i.e. for about 40 per cent of the complete observing programme. These two histograms show the differences in arcseconds between the $\alpha \cos \delta$ and δ from RGO and from INCA. The patterns are nearly symmetrical, with respective means of $-0\overset{''}{.}01$ and $0\overset{''}{.}05$ arcsec

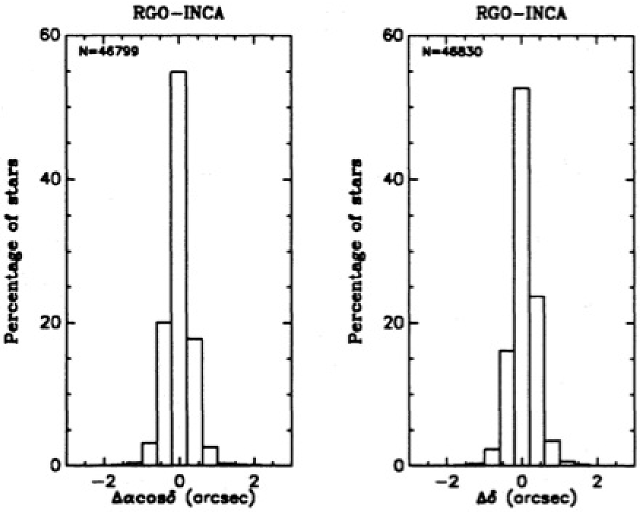

Fig. 1. Histograms of the differences between RGO and INCA in $\alpha \cos \delta$ and δ for the 47 000 considered stars

and widths* of about 0.3 arcsec. This is in agreement with the values obtained in Paper I and Lindegren et al. (1991), and confortably within the initial specifications of ESA recalled in Sect. 3.

The variations of these differences with equatorial and ecliptic coordinates are shown in Fig. 2 and 3 respectively. Some features are striking:

- $(\Delta\alpha \cos \delta)_\alpha$ and $(\Delta\alpha \cos \delta)_\lambda$ stay close to zero with almost no significant deviation (one exception is a negative $\Delta\alpha \cos \delta$, about $0\overset{''}{.}060$ arcsec, for α towards 3-4 hours, and about $0\overset{''}{.}080$ arcsec for λ towards 320°).

- $(\Delta\delta)_\alpha$ and $(\Delta\delta)_\lambda$ are almost always positive, with little significant variations.

- $(\Delta\alpha \cos \delta)_\delta$ and $(\Delta\alpha \cos \delta)_\beta$ show significant negative deviations in the southern hemisphere (δ between $-40°$ and $-60°$ and between $-10°$ and $-20°$, β between $-20°$ and $-50°$ and south of $-60°$), a significant positive deviation in δ towards $+20°$, and a possible trend in β, increasing from $-90°$ to $+90°$.

- $(\Delta\delta)_\delta$ and $(\Delta\delta)_\beta$ show a significant positive deviation between $-70°$ and $+30°$ in delta and between $-50°$ and $+30°$ in ecliptic latitude.

The variations of $\Delta\alpha \cos \delta$ and $\Delta\delta$ with respect to δ described above are very similar to the curves obtained by Lindegren et al. (1991) (Figs 4 to 7) for the differences 'sphere minus Input Catalogue', but also, to a lesser extent, for the differences 'sphere minus RGO'. They are, in fact, the differences between these two figures.

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* In order to characterize the scatter of these differences, a width based on distribution percentiles is used as dispersion estimate instead of a rms scatter, which is too sensitive to heavy tail distributions and outliers. This estimate is used even if the distribution is intrinsically non-gaussian but the result of the mixing of differences of positions with accuracies ranging from 0.03 (FK5) to 3 arcsec.

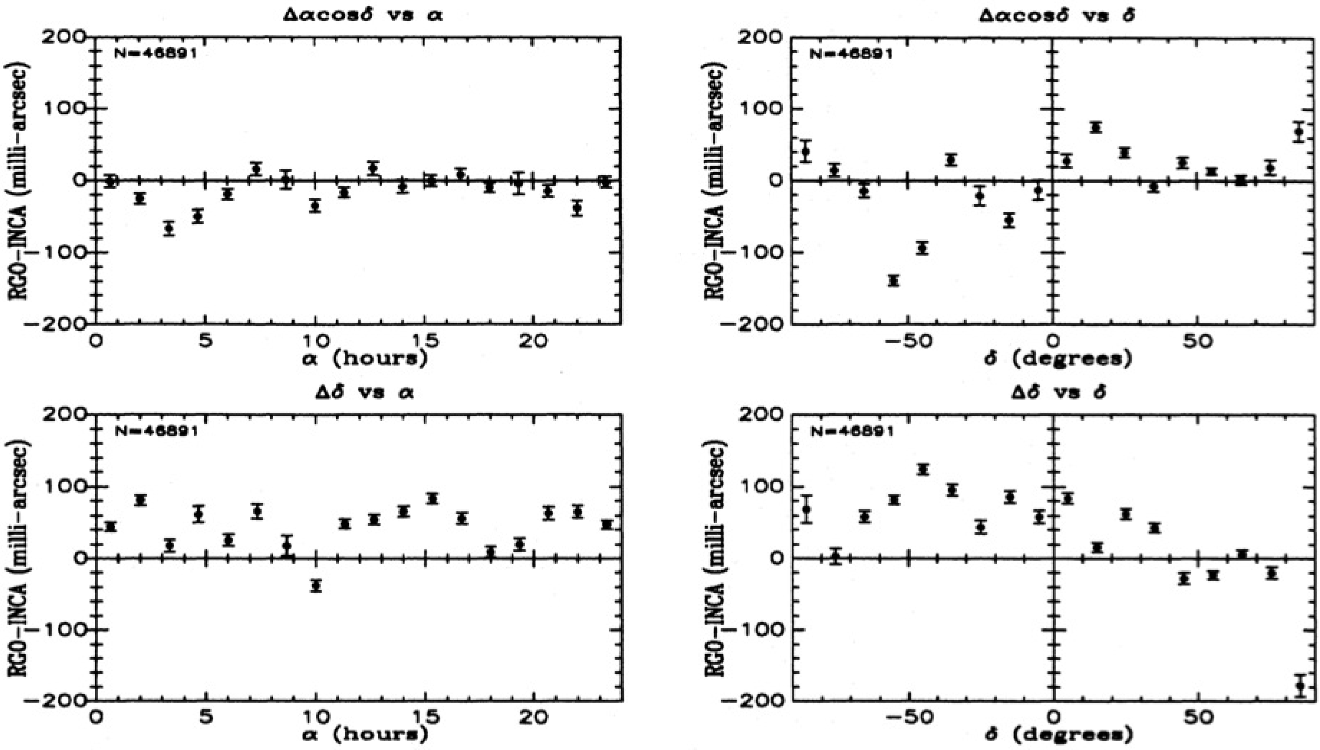

Fig. 2. Differences between RGO and INCA in $\alpha\cos\delta$ and δ for the 47 000 considered stars, as a function of equatorial coordinates; bins of 80 minutes in α, $10°$in δ; the error bars are standard errors on the averages estimated from the dispersion in each bin

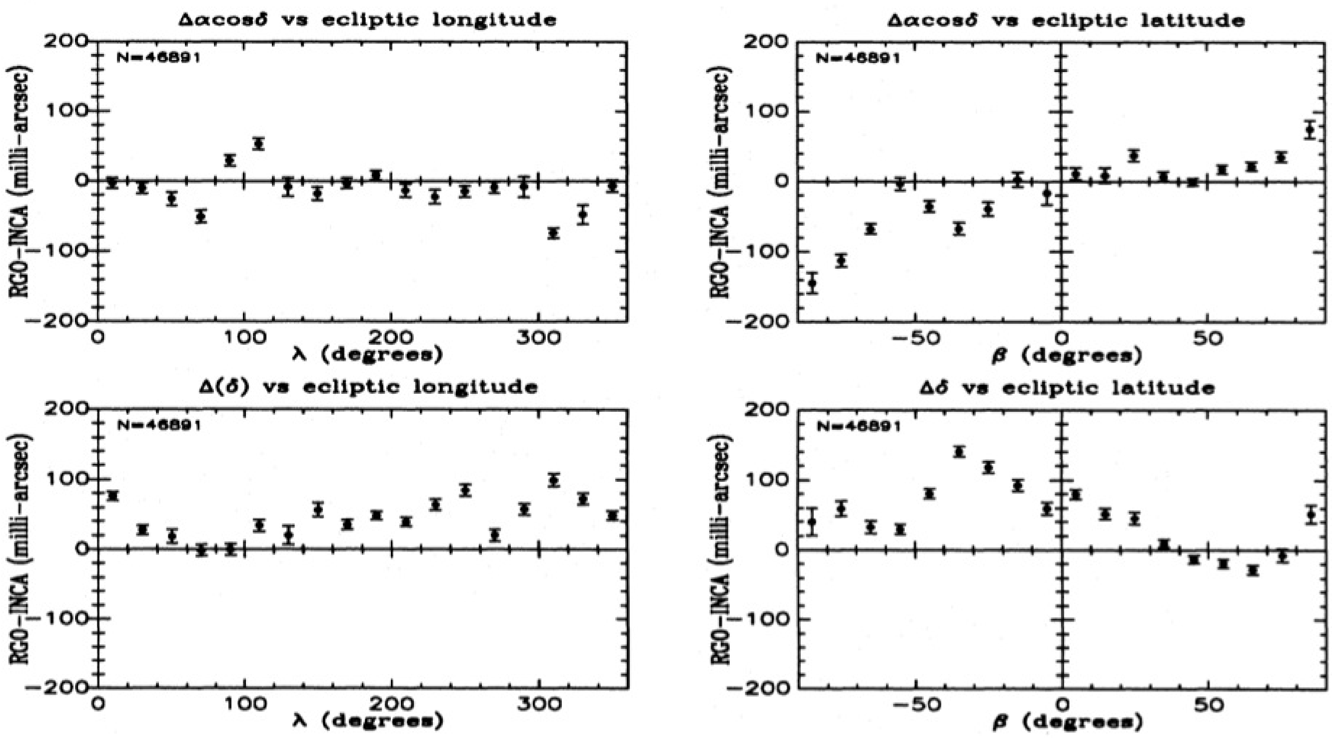

Fig. 3. Differences between RGO and INCA in $\alpha\cos\delta$ and δ as a function of ecliptic coordinates; bins of $20°$in longitude, $10°$in latitude

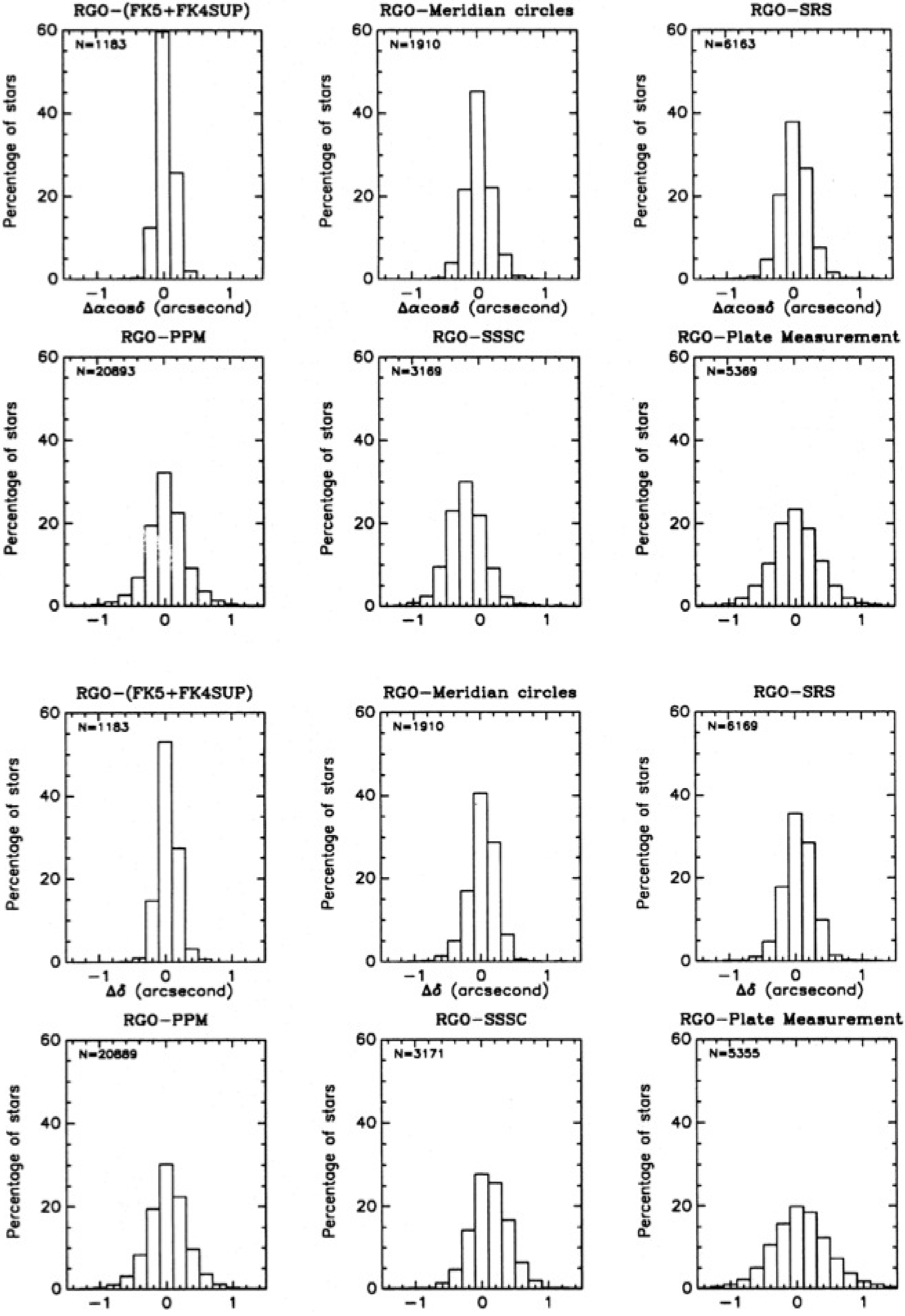
RGO-(FK5+FK4SUP)
N=1183
RGO-Meridian circles
N=1910
RGO-SRS
N=6163
Percentage of stars
Δαcosδ (arcsecond)
RGO-PPM
N=20893
RGO-SSSC
N=3169
RGO-Plate Measurement
N=5369
RGO-(FK5+FK4SUP)
N=1183
RGO-Meridian circles
N=1910
RGO-SRS
N=6169
Δδ (arcsecond)
RGO-PPM
N=20889
RGO-SSSC
N=3171
RGO-Plate Measurement
N=5355

Table 1. Median and width (arcsec) of distribution of differences between RGO and INCA in $\alpha\cos\delta$ and δ for each catalogue

	$\alpha\cos\delta$		δ	
	median	width	median	width
Meridian circles	0.01	0.18	0.03	0.19
SRS	0.03	0.20	0.05	0.21
PPM	0.02	0.26	0.01	0.27
SSSC	-0.21	0.26	0.10	0.27
Provisional CPC2	-0.16	0.33	0.13	0.29
Plate measurements	0.00	0.35	0.05	0.42

4.2. Comparison by source catalogue

The different source catalogues used in the Hipparcos Input Catalogue are considered here separately. The histograms of the differences between the RGO catalogue and each of these sources are presented in Fig. 4. The percentage of stars in each bin of $\Delta\alpha\cos\delta$ and $\Delta\delta$ with respect to the total number of stars in each source are given, in order to ease the comparison of the different figures. It shows clearly that SSSC catalogue is not centred.

Due to large scale systematic errors in the Input Catalogue, which could not be removed in the RGO Catalogue, the dispersion of the positions in the RGO Catalogue is about 0.09 arcsec as given by Lindegren et al. (1991). This prevents any direct comparison with FK5 since the order of precision of the positions given in this catalogue is about 0.04 arcsec. For the other catalogues, the comparison with the positional errors quoted in the Input Catalogue (Jahreiß et al. 1991) shows a close agreement (Table 1) and also gives an upper limit of 0.21 arcsec for the positional error of SRS catalogue at epoch 1990.

In order to understand the variations in equatorial and ecliptic coordinates, the possible effects of some specific catalogues was investigated. For example, the stars whose position sources were the SSSC (Sydney Southern Star Catalogue, King & Lomb 1983) and the provisional CPC2** (Nicholson et al. 1984, 1985), were eliminated from the considered sample. The resulting variations with respect to equatorial coordinates are shown in Fig. 5.

The most striking effect, when compared with Fig. 2, is to suppress completely the two dips in $\Delta\alpha\cos\delta$ versus δ (for $\delta = -50°$ and $-15°$). As a result, there is now a positive excess in $(\Delta\alpha\cos\delta)_\delta$ in the southern as well as in the northern hemisphere, which is reflected at all right ascensions (the differences stay negative only for α between 1 and 5 hours). This can probably be explained by the fact that the RGO catalogue is 'linked' to the Input Catalogue as a whole. If catalogues for which the mean deviation in $\alpha\cos\delta$ lies between $-0\rhd15$ and $-0\rhd20$ arcsec are not considered, the whole solution for the remaining stars is pushed towards positive values of $\Delta\alpha\cos\delta$.

This bias towards positive $\Delta\alpha\cos\delta$ (RGO-INCA) is also clearly visible in Fig. 4 for all source catalogues other than SSSC. As the central epoch of SSSC and provisional CPC2 is about 1960, the effect of 30 years of proper motion was investigated in order to explain this bias; it appeared that the bias remains present whatever the source of proper motions is (CPC, CPC2, SAO, SSSC, ...), with only slight variations. Therefore a possible explanation may be that some southern catalogues could be poorly linked to the FK5 system (since the FK5 catalogue does not show this bias). However, it should be kept in mind that this analysis is only tentative, being based on very preliminary results from the Hipparcos mission, and on only 12 weeks of observations (only about 300 stars from the FK5 are included in this comparison).

** Final CPC2 is presented in Zacharias et al. (1991)

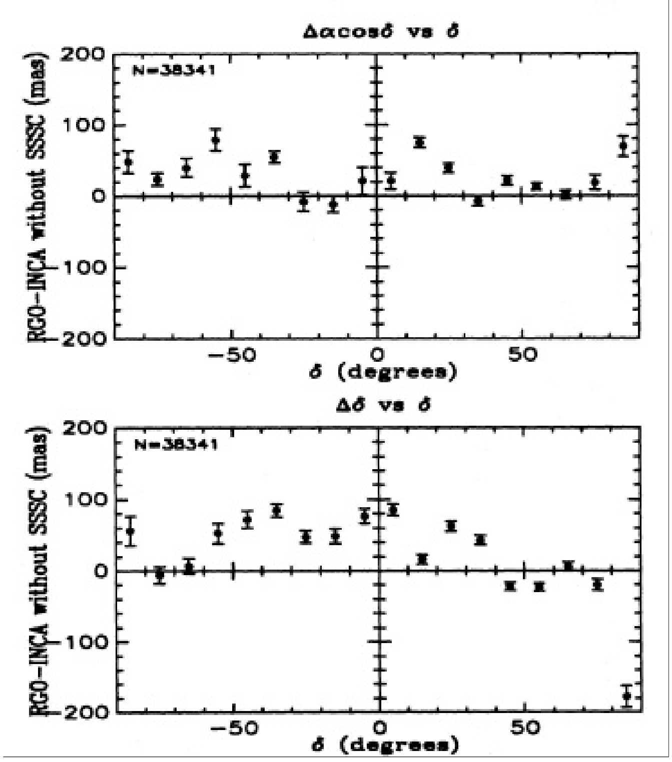

Fig. 5. Differences between RGO and INCA in $\alpha\cos\delta$ and δ for INCA stars, not considering stars whose source of position is SSSC or a provisional version of CPC2, as a function of δ

The suppression of the stars from the SSSC and provisional CPC2 also show up very clearly on the variations of $\Delta\alpha\cos\delta$ and $\Delta\delta$ versus β. These are shown in Fig. 6. A sinusoidal trend may be seen on both graphs, more marked on the differences in δ. Such an effect may come from the uneven coverage of the sky, or/and from the uneven range of orientations of the scanned great circles. This is still under investigation.

4.3. Single stars and double stars

The positions of double and multiple stars in the Input Catalogue are known to be less accurate than the positions of single stars. This is verified in the comparison with the RGO catalogue. Histograms of the differences RGO-INCA for double and single stars are given separately in Fig. 7: the widths are 0.27 arcsec for single stars or stars considered as single for Hipparcos observation (perturbation due to the secondary component(s) considered negligible), and 0.53 for double stars

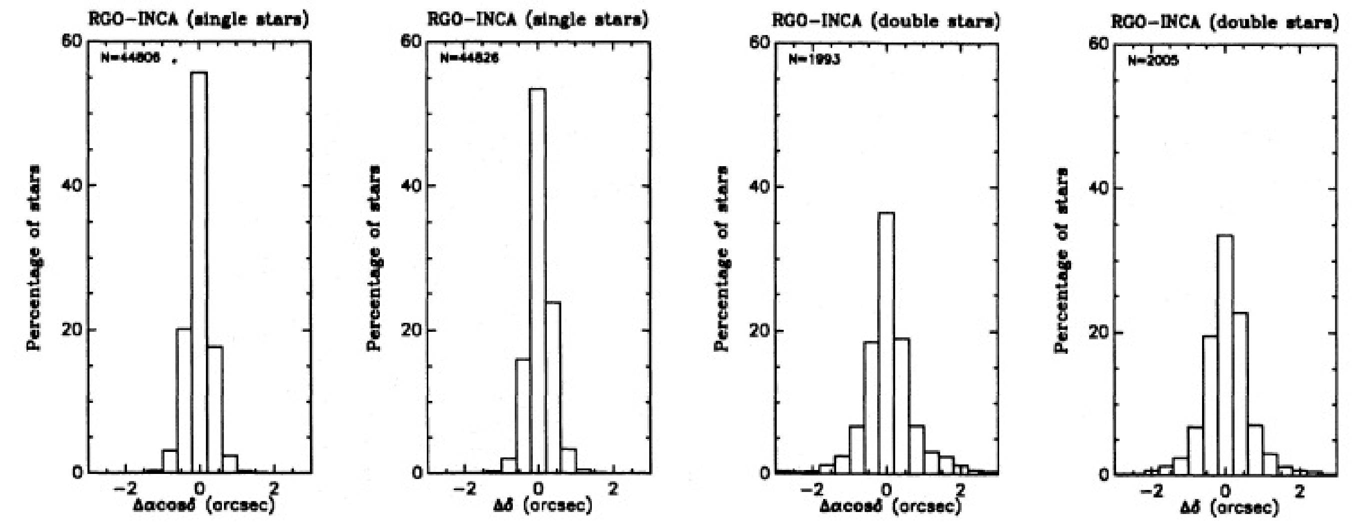

Fig. 7. Histograms of the differences between RGO and INCA in $\alpha \cos \delta$ and δ: single stars (left), double stars (right)

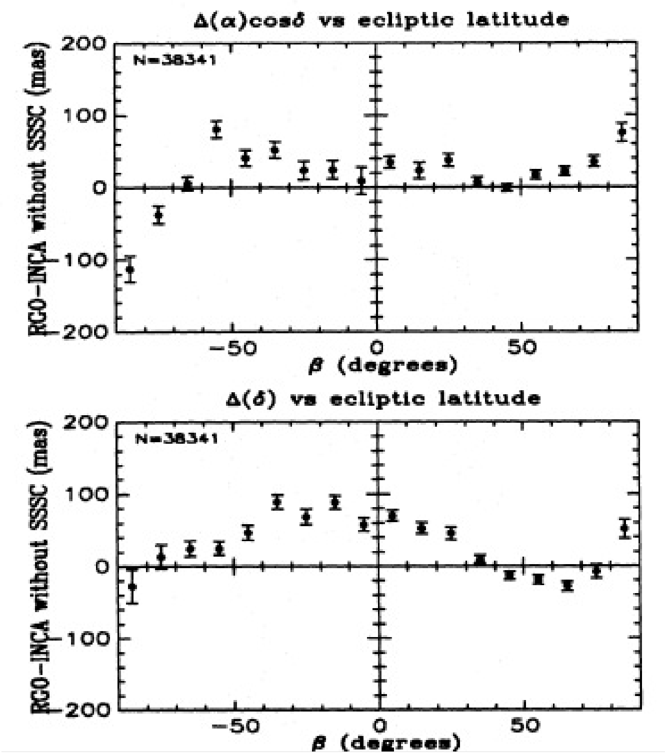

Fig. 6. Differences between RGO and INCA in $\alpha \cos \delta$ and δ for INCA stars, not considering stars whose source of position is SSSC or a provisional version of CPC2, as a function of ecliptic latitude

(two entries in the Input Catalogue, or one entry which is the photo-centre or the geometric centre of the system).

5. Comparison of the photometric data

A comparison has been made between the B_T and V_T as calibrated by the RGO team and as given by the INCA consortium. The three main sources of photometry in the Input Catalogue are respectively:

1) photoelectric photometry,

2) photoelectric V coming from the CAMC, and $B-V$ derived from spectral type and an extinction model,

3) V coming from very heterogeneous sources, mainly from visual observations, and $B-V$ derived from spectral type and an extinction model.

The difference between RGO and INCA photometry as a function of B_T and V_T magnitudes for these three main sources are presented in Fig. 8, 9, 11; medians and widths of these differences are indicated in Table 2.

1) In this preliminary version of RGO updated Catalogue, there is a small bias in B_T and V_T magnitudes, as can be seen in Fig. 8. This bias will soon be corrected; no special trend of the differences RGO-INCA with position (e.g. ecliptic coordinates) may be noticed.

Table 2. Median and width (magnitudes) of the distribution of the differences between RGO and INCA in B_T and V_T for the three major sources of photometric data in the Input Catalogue

	B_T		V_T	
	median	width	median	width
Photoelectric B & V	-0.010	0.055	0.000	0.040
Photoelectric V	-0.010	0.195	-0.020	0.075
Heterogeneous V	0.020	0.235	0.020	0.200

2) For stars from the CAMC, the colour was derived from spectral type and Fig. 9 shows the differences ΔB_T vs B_T and ΔV_T vs V_T. The method used to obtain colours may be tested on this sample as V_T is precise and does not introduce supplementary scatters in the estimation of the colours. The overall

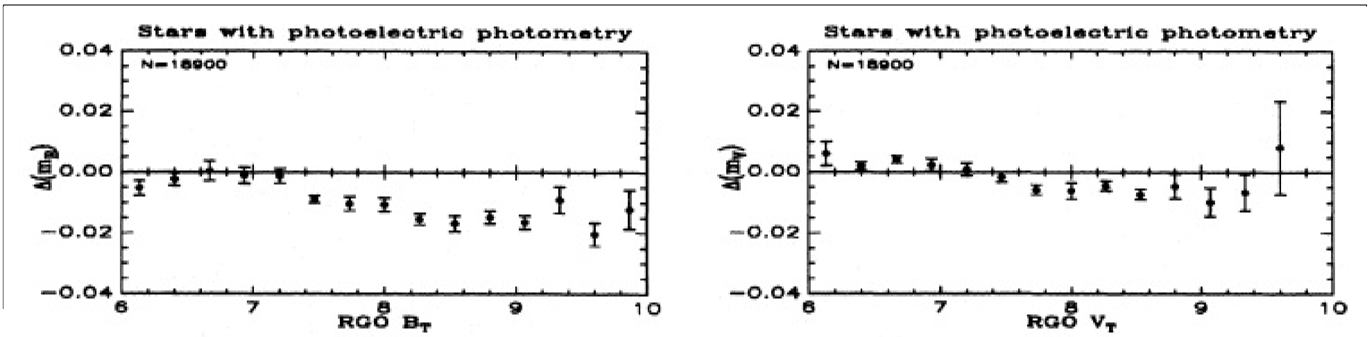

Fig. 8. Differences between RGO and INCA in B_T as a function of B_T and differences in V_T as a function of V_T for stars with photoelectric photometry and $V_T < 9.5$

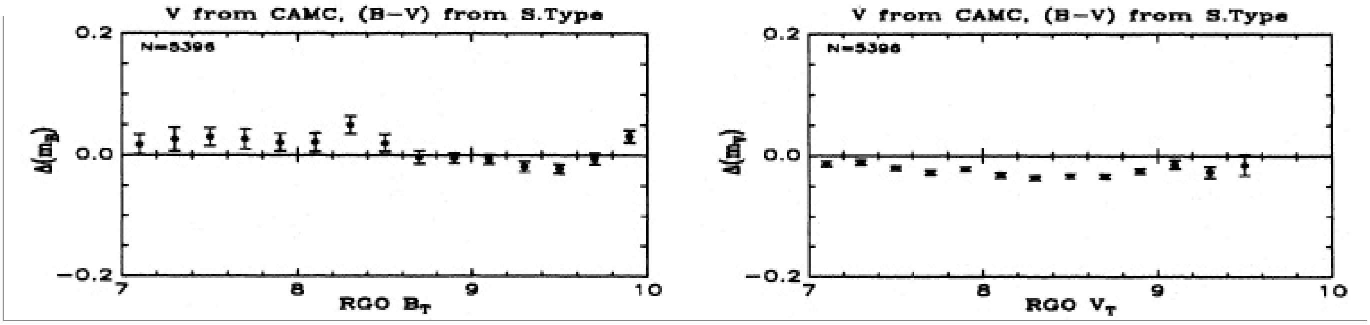

Fig. 9. Differences between RGO and INCA in B_T as a function of B_T and differences in V_T as a function of V_T for stars with photoelectric V and $B - V$ derived from spectral type

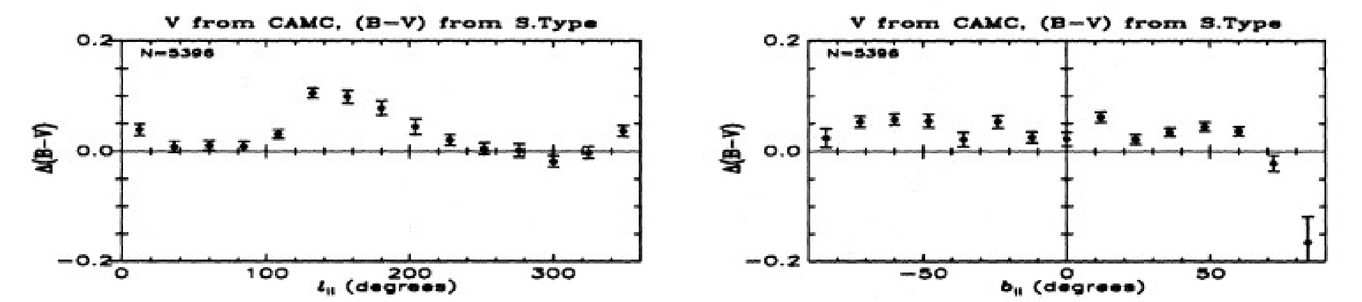

Fig. 10. Differences between RGO and INCA in $(B_T - V_T)$ as a function of galactic longitude and latitude for stars with photoelectric V and $B - V$ derived from spectral type

accuracy of colours obtained by this method is of about 0.18 (Tycho) magnitudes; however small systematic effects may be noticed when plotting the differences RGO-INCA as a function of galactic coordinates (Fig. 10): at north galactic pole, the negative differences is explained by a small number of stars with bad HD spectral classification, and wrongly considered as giants. Apart from this region, the differences are slightly positive due to distant stars (the model is less accurate for distances larger than 1 kpc) – this is especially visible between 140°-180°of galactic longitude; however there is also a contribution of erroneous spectral classifications.

3) Finally, stars which had photoelectric photometry neither in B nor in V are presented in Fig. 11. On the right side, it appears clearly how heterogeneous sources of photometry – mainly visual observations – systematically underestimate the magnitude. Without deriving the colour of these stars from their spectral type, the difference RGO-INCA in B_T (left side) would have had the same systematic trend (or even worse) as in ΔV_T.

6. Comparison of data on double stars

Double or multiple systems were given by the INCA Consortium as a single entry when the separation between components was below 10 arcsec. For systems with separation between 1.5 and 10 arcsec, the star mapper reduction is able to separate the components (Paper I). The comparison between RGO measurements and CCDM ground-based measurements is given in Fig. 12, both in separation and in position angle between components. Fig. 12 shows two perfect correlations, with median values/widths of 0⊳01⊲0⊳16 arcsec for differences in separation, and −0⊳04⊲2⊳5°for differences in position angle.

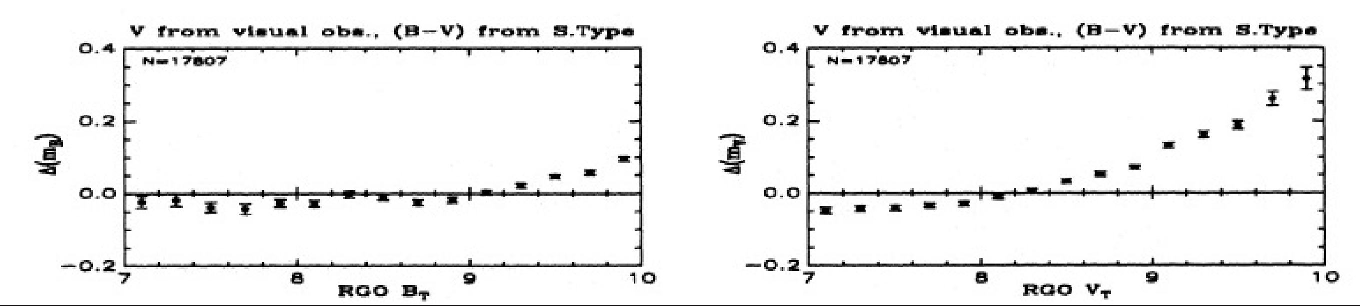

Fig. 11. Differences between RGO and INCA in B_T as a function of B_T and differences in V_T as a function of V_T for stars with heterogeneous sources in V and $B-V$ derived from spectral type

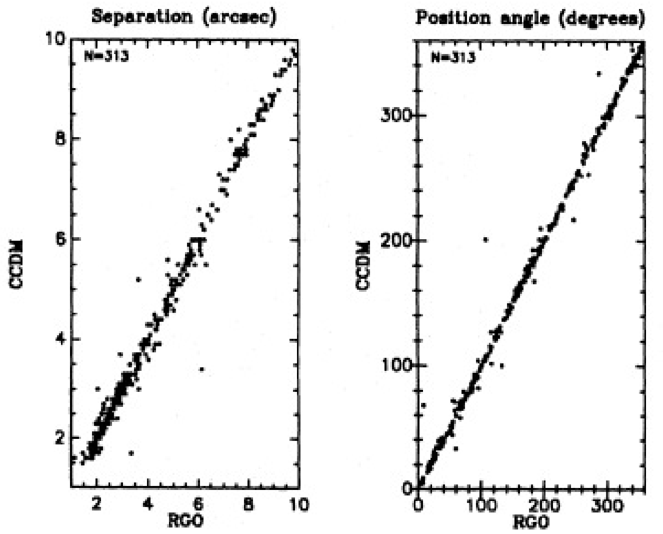

Fig. 12. Comparison between RGO and ground-based measurements of separation between components (left) and position angle (right) for double or multiple systems with $1.5\leq \rho \leq 10$ arcsec

7. Conclusion

Although preliminary, this work shows how fruitful is the collaboration between Hipparcos Consortia. The INCA Consortium, as supplier of the input data, improves its knowledge of the astronomical content of its data and, in return, the Data Reduction Consortia will probably find in these results some answers to questions appearing during the reduction process.

Apart from the minor effects described above, the preliminary data obtained from the Hipparcos star mapper are clearly consistent with most ground-based data; part of the updated positions are already used for the real time attitude determination of the satellite. Of course, they are still far from reaching the ultimately expected Hipparcos performances, and other questions (real positional accuracy of ground-based catalogues, systematic errors) will receive a definitive answer as soon as the comparison between input data and the sphere solution is done.

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