VIII

SCHMIDT ASTROMETRY

https://doi.org/10.1017/S0252921100021928 Published online by Cambridge University Press

The Future Utilisation of Schmidt Telescopes
ASP Conference Series, Vol. 84, 1995
J. M. Chapman, R. D. Cannon, S. J. Harrison and B. Hidayat (eds)

Schmidt-plate Astrometry – Dinosaurs in Action

Neill Reid

Palomar Observatory, Caltech, Pasadena, CA 91125

Abstract. Photographic plates are well established as stable detectors, well suited for positional astronomy. The completion of the current second epoch 48 inch Schmidt surveys in both hemispheres will provide material spanning baselines of 20–45 years, allowing proper motions to be determined to an accuracy of 4–7 mas yr^{-1}. This paper discusses some of the Galactic structure problems that these data, combined with accurate photometry, can be used to address.

1. Introduction

The main design advantage of the Schmidt telescope is that it provides high-quality images over a wide field of view. Until recently, the only detector that could make full use of the areal advantage was the photographic plate. From the point of view of astrometry, the glass plate is an excellent (and well tested) medium, providing very stable, long-lived information storage. However, photography has the disadvantage of both low quantum efficiency ($< 5\%$ overall) and relatively low photometric accuracy – areas where CCDs have substantial advantages.

Over the past 15 years, data from Schmidt plates have been widely applied to studying various aspects of Galactic structure. It is my opinion that, with the (literal) growth of CCD technology, these digital detectors (either on Schmidts or small, conventional telescopes) will supplant photographic data for virtually all of the photometric work. Astrometry, and, in particular, proper motions - is a different matter, since photography is building on over a century of plate material (half a century for large Schmidts). However, CCDs will probably take over this area too within the next 5–10 years, as is discussed further in the following section. For that reason I believe that it makes more sense to exploit currently available material and concentrate on small scale projects, rather than consider any further all sky surveys.

Photographic astrometry itself is a wide ranging field of research, so I propose to present only a selective review of three areas deserving particular attention. Other aspects have been dealt with in two recent conferences – Evans (1993) discusses the use of large-scale, proper motion data to study global Galactic parameters, such as the Oort constants; Majewski (1993) reviews recent work (mainly from 4 m photography) on the Galactic halo; and both Majewski (1994) and Scholz (1994) present orbital derivations for Galactic globulars and nearby dwarf spheroidals. I intend to concentrate nearer to home, and will discuss work

https://doi.org/10.1017/S0252921100021928 Published online by Cambridge University Press

on high proper motion stars; on open clusters; and on the nearby stars in the Galactic disk.

2. Which detector — CCDs or photographic plates?

Comparisons of old and new technologies (in any subject) can turn into emotive affairs, pitting (to stereotype matters) 'old fogeys using outdated methods' against 'young upstarts using unproven techniques'. However, in this case the operational parameters can be specified with reasonable accuracy (see also Monet 1994) :

First, photometry – it is extremely difficult to obtain magnitudes more accurate that $\pm$ 0.1 mag. from a *single* Schmidt plate (i.e. colours to $\sim$ 0.14 at best). Obviously, one can reduce the uncertainties by combining data from several plates, but at the expense of substantially more observing time. Typically, the uncertainties start to rise above $\pm$ 0.1 mag. within 3 magnitudes of the plate limit (P-3) and reach $\sim \pm$ 0.25 at P-1 – so the *effective* limiting magnitudes for UKST or POSS material are $R_F \sim 20.5$ or $B_J \sim 21.5$. Photographic photometry alone is not sufficiently accurate to answer unambiguously many important questions in Galactic structure – nor do Schmidt data penetrate to sufficiently faint magnitudes to set strong constraints on Galactic models (Reid & Majewski 1993). In comparison, one can achieve accuracies of $\sigma < \pm 0.05$ for $V < 19.5$ (and $\pm$ 0.1 at V = 20.5) from a 300 s CCD exposure on a 40 inch telescope.

Second, CCDs should provide more accurate image classification, since the linear response leads to a more accurate definition of the point spread function. The higher quantum efficiency gives added depth, although the corollary is that the lower dynamic range of CCDs demands separate, shorter exposures for brighter stars.

Third, astrometry – digital technology will eventually have a substantial impact in this area too, as evidenced by high-precision CCD parallax work (Monet et al. 1992; Tinney 1993), but at present these observations are restricted to relatively small fields ($\sim 5 \times 5$ arcminutes). Expanding coverage to larger areas demands scanning, and atmospheric effects are likely to limit the internal positional accuracy to $\sim$ 40 milliarcseconds (mas), without taking account of the problems involved in tying into the reference frame defined by bright stars (Monet, priv. comm.). The individual 48 inch Schmidt plate is, in fact, less accurate – COSMOS scans of POSS/UKST Hyades plates give uncertainties of $\sim$ 2–2.5 μm for $V < 15.5$ and twice that at fainter magnitudes (Reid 1993), while Monet (priv. comm.) measures similar uncertainties using the USNO PMM (note that both measuring engines have higher internal accuracies – the photographic plates limit the accuracy). However, one achieves these accuracies for an area of $\sim 6 \times 6$ degrees; the higher dynamic range makes it possible to tie into both a bright reference frame (e.g. TYCHO observations provide 10–20 stars per square degree) and to include measurements of significant numbers of faint galaxies; and, most important, these data can be combined with first epoch material (e.g. POSS I/II) to give baselines of 40 years or more. The result is that one can derive proper motions over a wide field that are accurate to $\sigma \sim$ 4–7 mas yr^{-1}.

https://doi.org/10.1017/S0252921100021928 Published online by Cambridge University Press

The main conclusion that I draw from these comparisons is that the best combination is to use CCDs for photometry and Schmidt data for astrometry (specifically, proper motion work). The second-epoch surveys that are currently underway in both hemispheres are likely to be completed by mid-1997 at the latest. If one includes the Whiteoak Palomar extension (to $\delta = -48^o$, 103aE only), then nearly three-quarters of the sky has Schmidt plates spanning baselines of at least 30 years. On this basis, since proper motion accuracy effectively increases linearly with time, there is little point in considering *large-scale* surveys for at least 10–15 years (by which time CCD astrometry may have taken over). For that reason, I will discuss using the currently available material, rather than future observing programmes.

3. Stars of high proper motion

Much of what we know about the Galactic stellar populations has been determined from analysing stellar catalogues derived from proper motion surveys. There are always questions raised about the importance of selection effects in these samples. Clearly, a proper motion selected sample is biased toward stars with higher space motions. However, if the selection criteria are defined accurately (and if one has even moderately accurate magnitudes and colours), one can allow for these biases in the subsequent analysis. The problem, until now, has been either that the selection criteria vary in some poorly constrained form as a function of position on the sky, or that the necessary ancillary data (mainly accurate magnitudes and colours) are lacking.

As an example, consider the Lowell survey (Giclas, Burnham & Thomas 1968 - LPM), which has formed the basis for a number of recent Galactic structure studies (Sandage & Fouts 1987; Carney, Latham & Laird 1989). This survey is based on 11 × 14 degree plates from the Lowell 13 inch and is limited to relatively bright stars, $B \lesssim 15.5$, but with significant field-to-field variations, and has a nominal proper motion limit of $\mu > 0''.27$ yr^{-1}. However, Luyten (1974) compared his observations against Lowell data for 3010 stars, 1131 stars with previously published motions and 1879 (then) unpublished. Both datasets show systematic offsets, but while the Lowell motions are higher by 0".02 yr^{-1} in the former case, the discrepancy ranges from 0".03 to 0".07 yr^{-1} for the latter sample. Subsequent comparisons (Cudworth 1990; Reid 1990 - R90) have shown that Luyten's astrometry is more accurate, $\sigma \sim 0''.007$ yr^{-1} versus $\sim 0''.025$ yr^{-1} for the Lowell data, so the net effect is that the LPM survey has a variable proper motion limit. Since the above mentioned investigations derive the tangential motions from the Giclas et al. catalogue (sometimes, as Majewski (1993) has pointed out, compounding problems by averaging Lowell and NLTT (Luyten 1979) motions), these systematic biases must affect the analysis of stellar kinematics.

The Luyten data themselves are no paradigm of perfection. Ryan & Norris (1991) have used the NLTT survey (($\mu > 0''.18$ yr^{-1}) as the basis of their halo survey, selecting stars with $m_R < 13$ and $m_{pg} - m_R < 0.9$. However, while the machine- and eye-measured motions are relatively accurate, the photometry is notoriously poor, with both zeropoint offsets and a substantial scatter, rising from ± 0.2 mag. at B = 14 to ± 0.4 or more at the Palomar plate limit

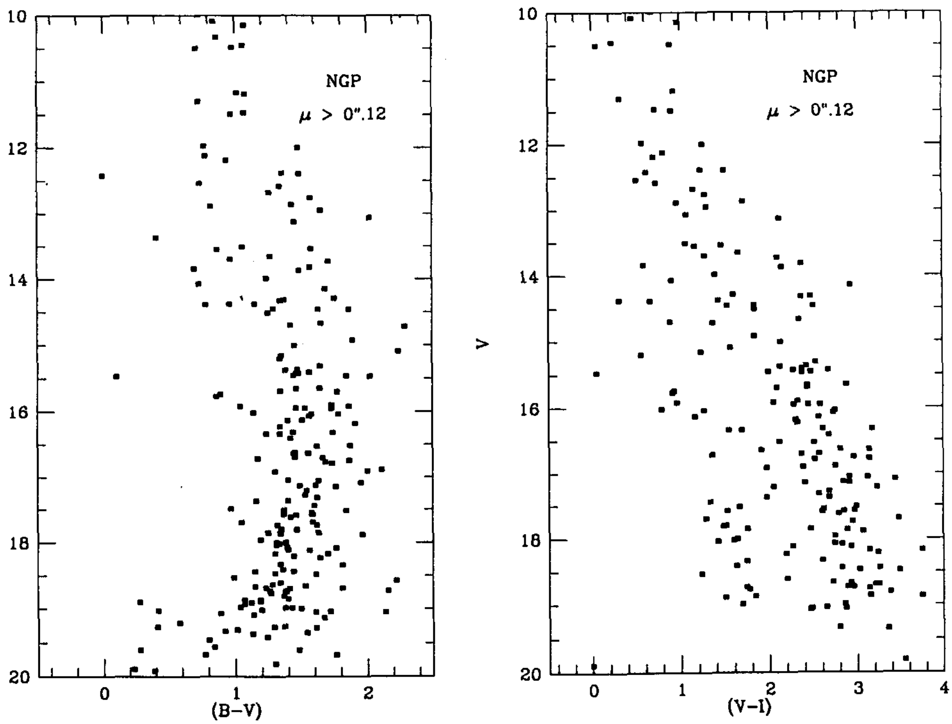

Figure 1. Colour magnitude diagrams for proper motion stars towards the NGP

(R90). Clearly, with this low accuracy photometry, considerable follow up work is required before any meaningful statistical analysis can be made.

We can improve matters considerably with current technology. Figure 1 shows colour magnitude diagrams for all stars with $\mu > 0''.12$ yr^{-1} towards the NGP (R90). These data are based on Palomar plates taken over a 20 year baseline, with proper motions accurate to 6–9 mas yr^{-1} and colours good to $< \pm$ 0.15 magnitudes. Evans (1992) has carried out similar analyses of APM data of four Schmidt fields, including a derivation of the white-dwarf luminosity function. These data can also be used to search for faint c.p.m. companions – à la VB 10 – to known nearby stars. We still require more detailed follow up spectroscopy (the surface density and magnitudes of these stars are well matched to a FLAIR-type Schmidt system), but these data provide a better defined sample for statistical analysis. The POSS I/II USNO astrometric catalogue (by D. Monet and collaborators) will obviously be ideal for this type of study.

There is one particular area which will not be tackled by conventional surveys – a search for stars of extremely high proper motion. Such objects, which are likely to be very low luminosity stars in the immediate solar vicinity, are difficult to cross-identify in most surveys due to the substantial motion between epochs, Luyten (1979), for example, limited his Palomar surveys to $\mu < 2''.5\ yr^{-1}$. On the other hand, most multiple-epoch surveys (e.g. Murray's (1986) SGC study) do not go deep enough to set interesting limits. The main requirement for this type of survey is deep plate material taken over a short time baseline, and an ideal source is the rejected plates taken for POSS II, many of which are scientifically useful. Kirkpatrick (Univ. of Texas) has started analysing COSMOS scans of multiple plates of nine fields. With baselines of 3–5 years, instead of 20+, he expects to detect all stars with $0.12 < \mu < 10''\ yr^{-1}$. Ruiz et al. (1988) have been carrying out a similar programme using plates from the (smaller) ESO Schmidt. Clearly, this type of project can be undertaken on other telescopes. Combining these data with the more conventional surveys, we should be able both to construct a more complete picture of constituents of the Solar Neighbourhood and derive stellar samples with quantified selection biases, better suited to investigating local kinematics.

4. Open clusters

Open clusters have long served as excellent laboratories for investigating the detailed processes of stellar evolution and have acquired particular attention in recent years as hunting grounds for sub-stellar brown dwarfs. In addition, the dynamical evolution of these systems is important for our understanding of the origins of the stellar populations in the Galactic disk. Theory leads us to expect mass segregation to develop, with lower-mass stars forming a broader halo around the more prominent, massive stars in the cluster core. At the same time, simulations show that stars evaporate from the cluster proper, developing a long sausage like structure – a moving group of stars with velocities only slightly different from the cluster stars, but not gravitationally bound to the cluster (Casertano, Iben & Shiels 1993). The Hyades moving group is the best studied (perhaps the only widely accepted) such system, and Eggen (1993) has estimated that as many as 2.5 % of the local stars are members of this extended system, which may contain 70 % of the mass of the original star forming region.

If we are to interpret correctly statistical cluster studies – such as searches for brown dwarfs – it is vital that we understand what are the relevant timescales for this dynamical evolution – how quickly does mass segregation develop? is there any primordial component to the segregation? how long does it take to destroy a cluster as a coherent spatial and/or kinematic entity? To address those questions demands detailed surveys which both cover a large enough area, and extend to faint enough magnitudes with accurate photometry, to obtain a fair sample of the lower-mass stars in the cluster halo. It is important to emphasise that, with field/cluster ratios of up to 1000:1 in the outer parts of clusters, eliminating non-members is the most difficult problem, requiring both accurate astrometry and photometry.

At present, such data exist for only two clusters, the Hyades (Reid 1993) and the Pleiades (van Leeuwen 1983; Hambly, Hawkins & Jameson 1991; Schilbach et al., this conference), although not even these two clusters have been surveyed completely. The COSMOS Hyades survey (which supplied the first unambigu-

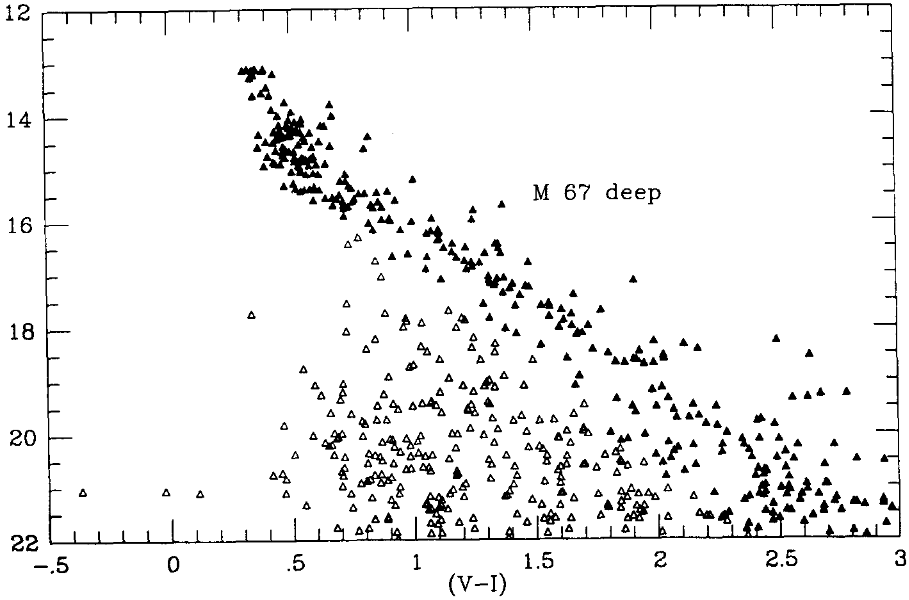

Figure 2. Colour magnitude diagrams for a field on the outskirts of M67

ous evidence of mass segregation in that cluster) covers only about half (~ 110 square degrees) of the cluster, van Leeuwen's catalogue is based primarily on astrographic plate material and becomes incomplete at $V \sim 13$, while Hambly et al. make no attempt to analyse the spatial structure. Other studies of open clusters either cover smaller regions in the cluster core (Stauffer et al. (1991-Pleiades), Jones & Stauffer (1991-Praesepe) or lack accurate photometry (Luyten's Palomar 48-inch surveys of Hyades, Pleiades and Praesepe).

The COSMOS Hyades data show that the currently available Schmidt plate material can provide the necessary astrometry for these detailed investigations. A forty year baseline gives proper motions accurate to ~ 4 mas yr^{-1}, well below the total space motions (relative to the mean of the local field stars) of clusters such as Praesepe ($\mu \sim 40$ mas yr^{-1}), α Per (~ 32 mas yr^{-1}), NGC 188 (~ 28 mas yr^{-1}) and even M67 (~ 30 mas yr^{-1}). At the same time, large format CCD observations can provide the photometric data necessary to eliminate most of the field stars. Fig. 2 shows a (V, (V-I)) colour-magnitude diagram for a 14 × 14 arcminute field on the outskirts of M67. These data were obtained using a Ford CCD on the Las Campanas 40 inch telescope as part of a study of the lower main sequence in several nearby open clusters (Hawley & Reid, in prep.), but since most of the accessible open clusters demand areal coverage of ~ 1.5 × 1.5 degrees, using CCD arrays on Schmidts is a viable alternative. The M67 main sequence is obvious, lying well to the red of most (but not all) field stars at

https://doi.org/10.1017/S0252921100021928 Published online by Cambridge University Press

faint magnitudes. The addition of accurate astrometry would permit further differentiation of field and cluster members.

5. Kinematics of the Galactic stellar populations

One of the major advantages of deep, Schmidt based surveys is that sufficient faint galaxies are detected to provide a reference frame for an absolute proper motion system. As a result, many larger scale features of Galactic structure are accessible to study. However, analysing (and interpreting) the data from these surveys is a substantial undertaking, reflected by the relative scarcity of published results. Nonetheless, amongst the problems tackled are:

- the vertical rotational structure of the disk – Murray's (1986) SGC survey revealed an apparent shear of ~ 36 km s^{-1} kpc^{-1} with increasing height above the Plane. I questioned this result, based on the R90 NGP data, but Majewski (1994) has shown that both datasets are consistent, while Evans (1992), Hanson (1987) and Kharchenko, Schilbach & Scholz (preprint) also confirm the shear.

- the rotation of the halo – extending above the disk, analysis of the NGP R90 astrometry suggests a retrograde halo. While other Schmidt studies (e.g. Soubiran 1993) fail to find this result, Majewski's (1994) deeper data show that retrograde rotation appears to set in at $z \sim 5$ kpc.

- the population structure of the disk – both Soubiran (1993) and Evans (1992) have attempted to deconvolve the contributions of separate stellar populations from (respectively) the velocity distribution and reduced proper motion diagrams (RPMD) constructed from their surveys, with particular emphasis on the elusive "thick disk". So far, however, the scope of these analyses is restricted, in that the conclusions derive from matching a particular 3-population (halo-'thick disk'-disk) model that is, in some sense, imposed on the data (see, in particular, Evans' RPMD).

All these problems require further study, particularly the last, which lies at the heart of understanding disk formation. Tackling them thoroughly requires not only astrometric data covering a wider range of (l, b), but also (to return to a common theme) accurate photometry for distance and abundance estimation.

6. Conclusions

The topic of this conference concerns the future of Schmidt telescopes. I have, perversely, concentrated more on science that can be derived from combining first epoch material with plates from surveys that will be completed in the next 2–3 years. There is little justification for undertaking a third epoch survey for 10–15 years, by which time plates (and even, perhaps, CCDs) will be obsolete. In the short term, however, photography is still the medium of choice for astrometry, and there are a number of smaller scale projects (such as searches for very high μ stars, or multi-plate surveys of individual fields) which should be undertaken. To exploit both these small scale projects and the survey analyses, it is essential that the astrometry is supplemented by accurate photometry and, in some cases, spectroscopy. It is in these complementary areas that CCD observations with Schmidt telescopes can make a very significant contribution.

Acknowledgements

I thank OCIW for access to the LCO 40 inch telescope. I have profited over the years from many discussions with Andrew Murray, while Dave Monet has been an entertaining source of enlightenment in recent years.

References

Carney B. W., Latham D. W. & Laird J. B., 1989, AJ, 97, 423

Casertano S., Iben I. & Shiels A., 1993, ApJ, 410, 90

Cudworth K. M., 1990, AJ, 99, 590

Eggen O. J., 1993, AJ, 106, 1885

Evans D. W., 1992, MNRAS, 255, 521

Evans D. W., 1993, in *Galactic and Solar System Optical Astrometry*, L. V. Morrison & G. F. Gilmore, eds

Giclas H. L., Burnham R. & Thomas N. S., 1968, Lowell Obs. Bull. 7, 67

Hambly N. C., Hawkins M. R. S. & Jameson R. F., 1991, MNRAS, 253, 1

Hanson R. B., 1987, AJ, 94, 409

Jones B. & Stauffer J. R., 1991, AJ, 102, 1080

van Leeuwen F., 1983, Ph.d. Thesis, Leiden University

Luyten W. L., 1974, *Proper Motion Survey with Forty-Eight Inch Telescope, XXXVIII*, (Univ. of Minnesota, Minneapolis)

Luyten W. L., 1979, *NLTT Catalogue*, (Univ. of Minnesota, Minneapolis)

Majewski S. R., 1993, ARA&A, 31, 575

Majewski S. R., 1994, in *Astronomy from Wide-Field Imaging*, Proc. IAU Symp. 161, (Kluwer, Dordrecht), in press

Monet D. G., 1994, in *Astronomy from Wide-Field Imaging*, Proc. IAU Symp. 161, (Kluwer, Dordrecht), in press

Monet D. G., Dahn C. C., Vrba F. J., Harris H. C., Pier J. R., Luginbuhl C. B. & Ables H. D., 1992, AJ, 103, 638

Murray C. A., 1986, MNRAS, 223, 649

Reid I. N., 1990, MNRAS, 247, 70

Reid I. N., 1993, MNRAS. 265, 785

Reid I. N. & Majewski S. R., 1993, ApJ, 409, 635

Ruiz M. T., Maza J., Mendez R. & Wischnewsky M., 1988, ESO Messenger, 54, 36

Ryan S. G. & Norris J. E., 1991, AJ, 101, 1865

Sandage A. & Fouts G., 1987, AJ, 93, 74

Scholz R. D., 1994, in *Astronomy from Wide-Field Imaging*, Proc. IAU Symp. 161, (Kluwer, Dordrecht), in press

Stauffer J. R., Klemola A., Prosser C. & Probst R., 1991, AJ, 101, 980

Soubiran C., 1993, A&A, 274, 181

Tinney C. G., 1993, AJ, 105, 1169

Discussion

Stobie: We have two very different figures for the limit of astrometric accuracy with photographic emulsion. Neill Reid quoted 2–4 μm for Schmidt plates. This morning Barry Lasker quoted ~ 0.2 μm, a factor of 10 smaller. My understanding is that the latter figure is based on the work of Van Altena and Lee as a theoretical limit, which was also confirmed with 4 m telescope prime focus plates. My question is, why does a Schmidt telescope photograph not come anywhere near this theoretically expected limit?

Reid: I think that there are at least two contributing factors. First, there may be small scale wrinkles in the reference frame, on scales of one to several cm. Second, the algorithm used for centroiding individual objects is very different for the Schmidt/COSMOS data as compared with the 4 m PDS measurements.

Lasker: Following on the theme of possible centroiding effects, I would note that most of the astrometry we've considered was done with either a centre-of-gravity centroider, or a Gaussian fit. Neither is a particularly good choice for the small images that we find on plates from the Palomar and UK Schmidts. There are other approaches that I feel merit further attention; a reflective auto-correlation technique (see Le Poole, *Minutes of the IAU photographic Working Group*, Munich 1988), and a cross-correlation method based on modelled images (Lanteri et al. in Potsdam). I would also note that in another discussion at this meeting, Murray called attention to the spiral search method used in the now retired GALAXY machine (Fellgett, Optics Tech, 1970, 2, 61). It is particularly interesting that Murray reports that UK Schmidt plates so processed, appear to admit a simple plate model.

Murray: If the fainter stars are evaporating from the Hyades cluster, then we should expect the convergent points of proper motion to be different for the bright and faint stars, thus imitating the convergent point method used for determining distances to individual stars.

Reid: I believe that is true if there is a net expansion amongst the lower mass stars, although the mean motion may be below the detection limit.