# CCD Astrometry. No, Really – It is Interesting!

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## Introduction

In recent years, the field of astrometry – usually considered a stuffy backwater by most astronomers – has been revitalized by the introduction of CCDs into general astronomical use. Not only have these devices made photographic plates outdated for most astrometric purposes, but they have significantly advanced the precision with which astrometry can be done. In the process they are turning astrometry from a field dominated by large, long-term measurement programmes and endless reductions of celestial co-ordinates, into a vital and fundamental contributor to current research programmes. In this article, I'd like to show what CCDs can (and can't) be used for, why they are so much better than photographic plates, how easy it is to do astrometry with them, and to look at where progress in this field can be expected to go.

## What CCD Astrometry Can't Do

Of course, no device is perfect, and there are some astrometric applications for which CCDs have not proved successful. Perhaps the most serious unsolved problem is that of dynamic range. Whereas photographic plates can be successfully used for astrometry when the cores of images are saturated, no technique has yet been devised which allows saturated CCD images to be centroided with the same precision as unsaturated images. This is a major problem for the astrometry of distant and bright objects, like Galactic giants, supergiants and AGB stars – these include, of course, the distance-indicator objects everyone would like to obtain parallaxes for; Cepheids and RR Lyrae stars.

The difficulty is that these stars are intrinsically very bright, and rather rare. So, within a given CCD field-of-view the number density of stars suitable for use as reference objects is very small – to obtain sufficient counts on the intrinsically fainter background stars requires saturating the programme object. Photographic programmes deal with this by the deposition of uniform Nichrome attenuation spots onto filters mounted against the plates, allowing selective dimming of the programme star. However, astrometric results with the precisions attained by CCD programmes have yet to be obtained with any magnitude compensation system and a CCD. This means that while CCD astrometric programmes can obtain parallaxes to more distant stars than photographic programmes, they can only do so for relatively faint ($V \gtrsim 15$) magnitudes.

The second difficulty with CCDs is the limited size in which they are currently available. Photographic plates can be purchased (at least for the immediate future) in sizes up to ≈ 400 mm on a side. The largest CCDs currently available are more like 50 mm in size. This means that CCDs cannot be used for applications requiring wide-angle (i.e. ≳ 20–30′) astrometry. However, this may not be as serious a problem as it seems. Studies of the astrometric effects of the atmosphere have shown that the residuals produced in astrometric solutions increase with the FOV used and decrease with exposure time (Han 1989, Monet & Monet 1989). This means that for useful exposure times (~ 1000s), solutions for reference frames in fields of ≈ 20′ never get much better than ≈ 10 mas[1] – and this uncertainty scales roughly as both the one third power of field size and inversely with the square root of the exposure time. This means that for large fields of view (~ 1°), the limiting precision is set by the atmosphere, not the detector, and the use of CCDs may produce no gain. It also implies that taking short exposures in order to avoid the saturation problems described above significantly degrades astrometric performance.

## What CCD Astrometry Can Do

So, those are the minuses – you can't measure very bright stars, and you can't measure very large angles. However, those are exactly the classes of object for which HIPPARCOS will be producing superior astrometric data in the next few years in any case. It is in measuring faint objects – objects which HIPPARCOS can't reach – that ground-based CCD astrometry really finds its niche.

Perhaps the biggest advantage which CCDs provide for astrometry is that since CCD data are inherently digital, they can be easily evaluated as observations are being carried out. In particular, this means that the observer can examine test images, and place the programme object back in exactly the same location on the telescope's focal plane as the last epoch's observations. The immediate result of this is to allow CCD astrometry to be almost purely differential – except for applications requiring the highest of precision, the telescope's field distortion becomes irrelevant.

Second, CCDs have much higher quantum efficiencies than photographic plates – allowing the observation of objects ~ 3 magnitudes fainter for a given telescope and observing conditions. In particular, they are more sensitive in the red. This latter point is especially important because the astrometric effects of the atmosphere become less severe when observations are made at red wavelengths.

And lastly, because the matrix of pixels in modern CCDs are so regular, and charge-transfer efficiencies are so good, the precision of centroiding becomes almost photon-counting limited – the more photons you collect the better your position comes. This allows images to be centroided to hundredths of an image size. Photographic plates, on the other hand, have an irregular matrix of grains, and they also must be digitized with a measuring machine, with all the mechanical uncertainties that those machines introduce. It should be noted, though, that centroiding to this precision requires that all the objects have the same point-spread-function, that is they must be unresolved. (This has important implications for the astrometry of the very distant objects. If extragalactic reference objects are required, they must be QSOs – galaxies will not do.)

Taken together, these advantages allow astronomers to acquire astrometry at the several mas-level in a very straightforward manner, using the common-user CCD instruments now available at most telescopes. Moreover, they allow more dedicated astrometric programmes to push precisions below the mas-level. The pioneers in this field have

[1] "mas" is used as an abbreviation for milliarcsecond throughout.

been the US Naval Observatory's Flagstaff station, which has been carrying out a CCD parallax programme since 1983 (see Monet et al. 1992). This programme has been so phenomenally successful, that it has led to the termination of the observatory's long-running photographic programme. Its success has also led to the initiation of smaller astrometric programmes at other observatories – most notably, Mt. Stromlo (Ianna 1992), Cerro Tololo (Ruiz et al. 1991) and Palomar (Tinney 1993a).

These programmes, however, have been significantly different from most previous astrometric programmes. To some extent, astrometric programmes have traditionally been carried out on dedicated, small aperture telescopes and have targetted large numbers of stars. They have tended to be run as a "service" to the astronomical community, rather than with a specific and immediate scientific goal in mind. The ease of doing astrometry with CCDs, however, has changed that. The smaller programmes listed above have all been scientifically motivated, and targeted at particular classes of objects of interest to the astronomers concerned. In short, they are no different from any other type of astronomical project.

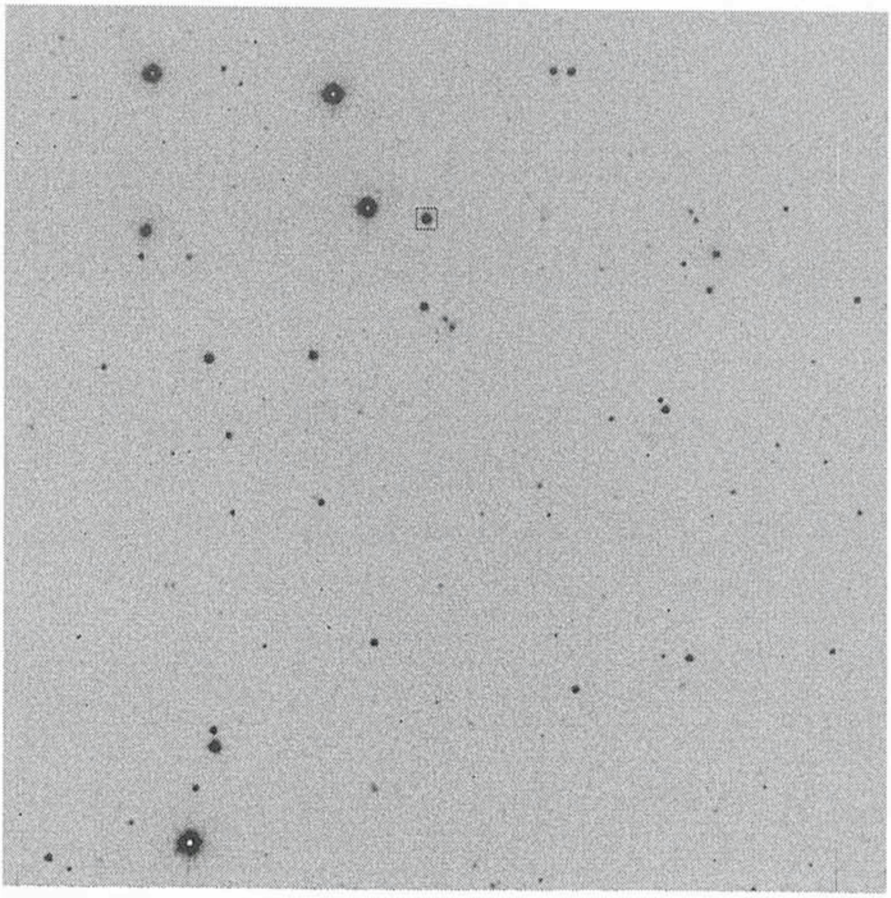

Figure 1: *A typical CCD frame of the recently discovered VLM star TVLM513-46546 (north is up, west to the left. The object is marked with a box).*

## "Do-It-Yourself" Parallaxes

The Palomar Parallax programme was motivated by the need for more parallaxes for the very faintest of main sequence stars. A photometric survey for these stars (Tinney 1993b, Tinney, Reid & Mould 1993), had indicated a need for more Very Low Mass (VLM, $M \lesssim 0.2M_\odot$) stars with measured distances, in order to define the colour-magnitude relations essential for photometric selection of these stars. The USNO's results encouraged us to try and obtain these parallaxes for ourselves, rather than rely on their heavily overburdened programme.

Observations were carried out at five epochs per year (roughly evenly spaced throughout the year so as to provide good sampling of our VLM survey fields), with the Palomar 60″ (1.5-m) telescope. The CCD used was a Tektronix 1024×1024 thick, front-side illuminated device. When mounted at the Cassegrain focus of the 60″ the CCD's 24μm pixels gave a scale of 0.372″/pix. The field-of-view then was ≈ 6′ – this was found to be sufficiently large to provide a good background reference frame of stars for our programme objects, which were situated at b ~ 40° – 60°. All observations were carried out through a Gunn i filter ($\lambda_{eff} \approx 790$nm, $\Delta\lambda \approx 100$nm). The choice of this filter was motivated by several factors; first, the target stars were all extremely red, making observations at as long a wavelength as possible desirable; second, the effects of atmospheric differential colour refraction are minimized by observing in the red; and third, as the CCD used was frontside illuminated, observing at a red wavelength reduces the sub-pixel effects of observing through the CCDs frontside gate structure.

Multiple images (3–4) of each programme object were obtained at high parallax factors several times a year. Some effort was made to place objects at roughly the same location on the CCD at each epoch. All the data were flattened with dome flats. The stellar images were centroided using DAOPHOT – we found that each observation could be centroided to about 1/200th of an image size. That is, for a star of I = 16.5, a single 300s exposure in 1″.0 seeing gives a position good to ≈ 5 mas. (Observations were not carried out in seeing worse than 2″.5 – it was found to be not worth the time spent reducing the data). All our observations were mapped onto a common coordinate system using a reference frame of background stars – since our programme objects are intrinsically very faint, an average background star of similar magnitude is more than 100 times further away, making corrections from relative to absolute parallax very small. A sample CCD frame for one of our programme objects (TVLM513-46546) is shown in Figure 1. Figure 2 shows its preliminary astrometric solution as derived in Tinney (1993a). Over the 2 years for which data have been reduced to date we typically obtain parallaxes with 2–3 mas uncertainties. Over the total 3 years which our programme will run (observations will terminate in November 1993) we expect to obtain parallaxes with uncertainties of 1–2 mas. For the one object we have measured in common with the USNO (VB10), agreement was found within our estimated 1-σ uncertainties (Monet et al. 1992).

The greatest problem to surmount in carrying out a parallax programme for these stars, is dealing with the effects of differential colour refraction (DCR) – put simply, the reference stars have a shorter effective wavelength through the Gunn i filter than the much redder programme stars. This results in the programme stars suffering less atmospheric refraction than the reference stars. However, so long as observations are made reasonably close to the meridian, this effect can be substantially corrected. We do this by observing each object as it rises and sets on a single night. The motion introduced by DCR can then be measured and calibrated out on subsequent nights. We found

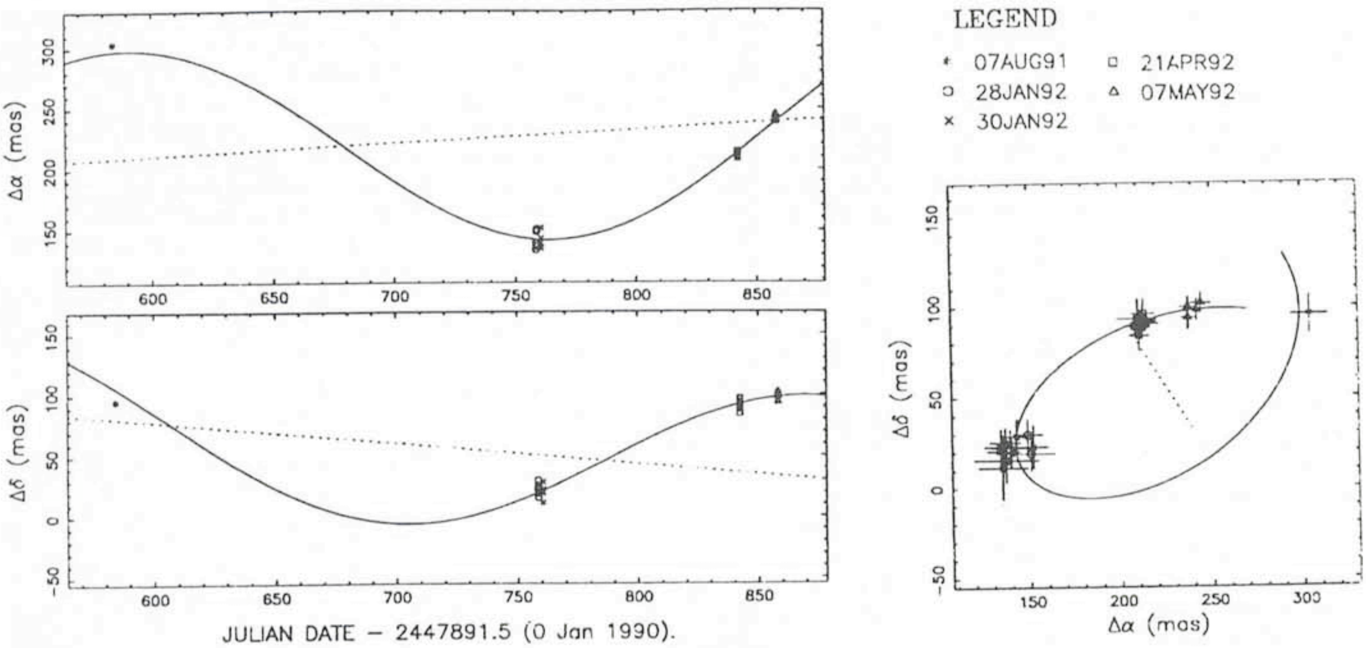


Figure 2: *The preliminary astrometric solution for this object (Tinney 1993a).*

that our use of a Gunn i filter gave us a significant reduction (a factor of about 4) in the amount of DCR observed, compared with that seen at the USNO, where a much wider filter ($\lambda_{\rm eff} \approx 690$ nm, $\Delta\lambda \approx 300$ nm) is in use. This means that while we need to take longer exposures, we have considerably more flexibility in scheduling, since we can observe $\approx 4$ times further from the meridian for a given DCR effect. For a non-dedicated facility this flexibility is important. In any case, longer exposures allow differential seeing effects over the field of view to be averaged out and therefore increases astrometric precision.

Figure 3 shows how this small programme has been able to make a significant contribution to the specific problem it was designed to address. The first panel shows the colour-magnitude diagram as it existed when our VLM survey was begun, the second shows it as of earlier this year. Almost half of the VLM stars ($M_{\rm Bol} > 13$) which now have parallaxes come from the Palomar programme. It is also worth noting that by carrying out our own parallax observations, this improvement could be obtained quite quickly – the total time between the identification of TVLM513-46546 as a VLM candidate and the measurement of its absolute magnitude (it is the second faintest VLM star known) was only 18 months.

## Pushing Back the Envelope

If "common-user" astrometric programmes can obtain results at the several mas level over only a few years, what are the prospects for specialized programmes to achieve higher precisions? Currently, the barrier preventing sub-mas astrometry is the atmosphere – both due to differential colour refraction, and due to differential seeing effects. The obvious solution is to carry out astrometry from space with a CCD camera, something the corrected HST may be able to do. But in the nearer term, what can be done from the ground? It turns out that there are a number of regions in the "observing phase space" which have yet to be fully explored, and which may produce some exciting new results.

Higher precisions can be achieved by observing reference frames over smaller fields of view, so long as a rich enough field of unresolved objects is available to transfer all the data onto a common coordinate system. Narrow-band filters, longer integration times and larger telescopes should be used to minimize the atmosphere's effects whenever possible. Sites with superior seeing should obviously also be preferred. By taking advantage of all these, it should be possible to push the astrometry of faint objects below the 1-mas barrier.

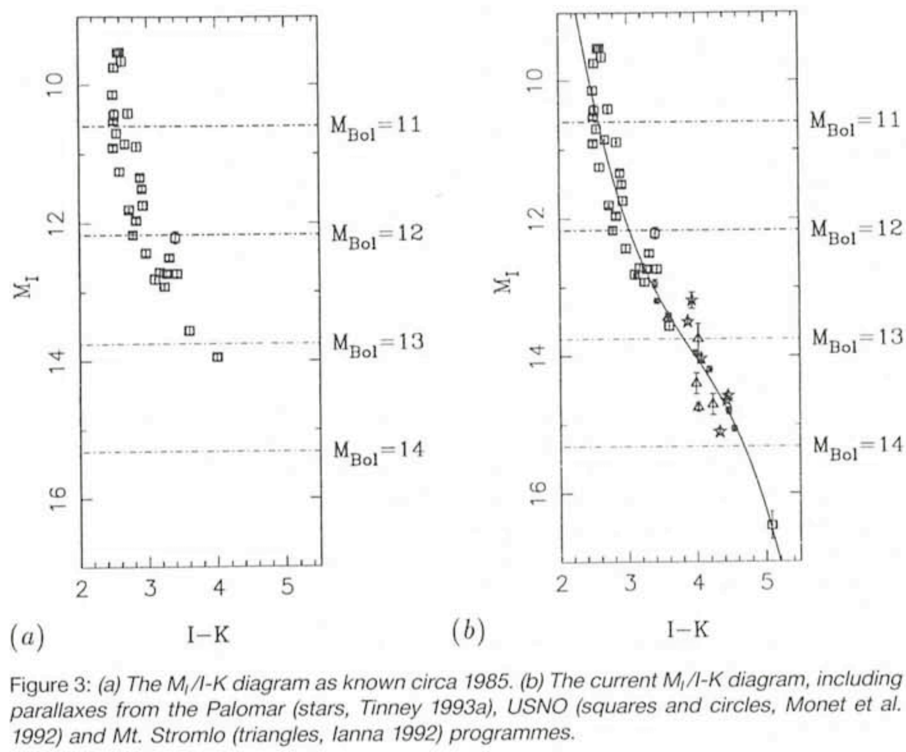


Figure 3: *(a) The $M_I$/I-K diagram as known circa 1985. (b) The current $M_I$/I-K diagram, including parallaxes from the Palomar (stars, Tinney 1993a), USNO (squares and circles, Monet et al. 1992) and Mt. Stromlo (triangles, Ianna 1992) programmes.*

Figure 1: *ESO 50-cm telescope with the TV guiding system of FLASH. The total weight of the guiding system is only about 35 kg. It contains the fiber-fed interface, comparison lamps and a conventional SIT low-light-level camera.*

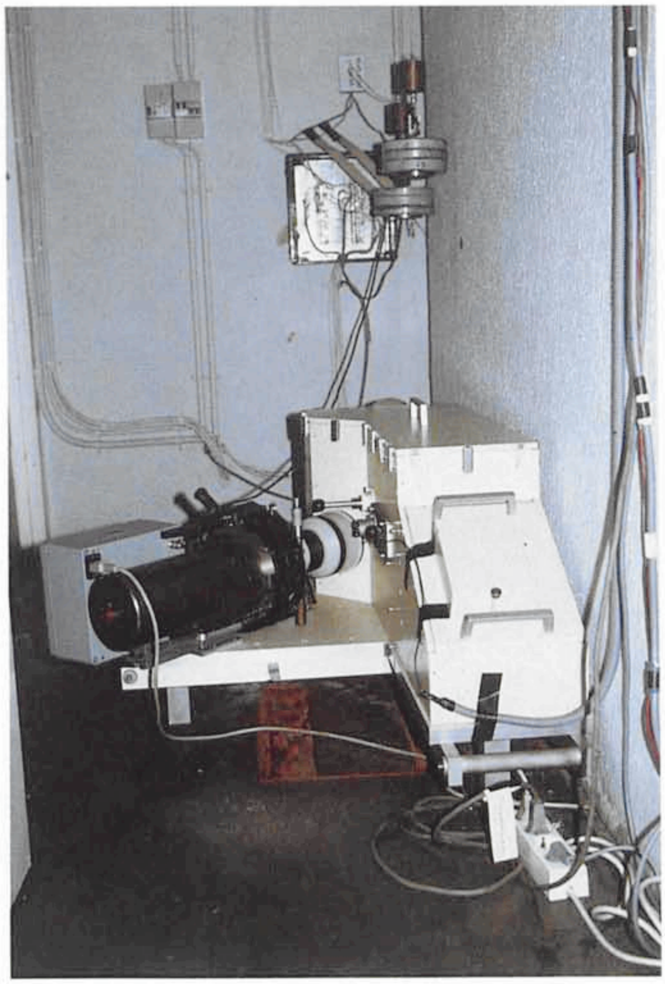

Figure 2: *Our spectrograph with CCD and CCD electronics, in the small cabin at the concrete base of the telescope, the smallest coudé room in the world. In the background some counterweights of the telescope balancing system can be seen.*

plifies the merging of the reduced different echelle orders. One also eliminates flexure problems while housing the instrument in a temperature and humidity controlled room. During observing at the ESO 50-cm telescope the spectrograph was placed in the small cabin at the concrete base of the telescope behind the astronomers office with only two connections to the outside world, one incoming fiber and one outgoing coaxial cable.

With an efficient detector, stars down to a magnitude of 7 are in the reach of the ESO 50-cm telescope. Using an EEV CCD with 1252×770 pixel of 22 μ, we get 2700 Å in one exposure. At standard setup we selected the wavelength range from 4050 to 6780 Å. This setting allows observations of 57 echelle orders simultaneously, with a generous overlap between the orders. With a 100 μ fiber, which corresponds to 2."75 at the ESO 50-cm telescope, the spectral resolution is about 20,000. During observation, up to 100 CCD frames (including ThAr- and flatfield-spectra) can be stored on the hard disk of the CCD control computer. These frames are transferred to magnetic tapes each morning and later copied to DAT-tapes by ESO.

## Luminous Blue Variables

Apart from supernovae at outburst LBVs are the most luminous stars in the Universe ($M \approx -9$ to $-11$). For more recent reviews see Wolf (1992) and Stahl (1993). The LBVs have recently been recognized as keys in connection with the evolution of massive stars. At quiescence they define an inclined instability strip of OB supergiants (Wolf, 1989) close to the Eddington limit. They are characterized by photometric variations of 1 to 2.5 mag in timescales of years and longer. At maximum brightness they are surrounded by cool ($\approx 8000$ K), dense ($N \approx 10^{11}$ cm$^{-3}$) slowly expanding ($v \approx 100$ km s$^{-1}$) envelopes of typically equivalent spectral type A. In addition to the large outbursts, photometric microvariations of 0.1 to 0.2 mag on timescales of 1 to 2 months or more have been found in all those cases observed in more detail (van Genderen, 1989).

During the past decade our group has observed spectra of the established and newly discovered LBVs of the Galaxy and of the Magellanic Clouds more or less regularly each year at La Silla with CASPEC. The exhibited long-term spectral variations shown by the LBVs have been of vital importance for a better understanding of the outburst phenomenon. They have contributed quite considerably to derive the general picture sketched above. On the other hand, with snap shot observations, typically separated by one year, the detailed hydrodynamic processes cannot be studied.

## The Campaign

For a better understanding of the atmospheric motions, systematic spectroscopic monitoring over a time span of months with good resolution in wavelength and time is badly needed. We therefore applied for two contiguous observing runs of two months each at