CHAPTER 12
CCD ASTROMETRY

It is now many years since CCD (charge-coupled device) astrometry replaced the photographic plate for astrometry. In practice all astrometry these days is performed with CCD and associated technology, the one possible exception being the measurement of photographs of meteors, which are still commonly recorded on photographic film – although it is probable that the CCD or similar technology will soon replace photographic films even for the measurement of meteors. This chapter, therefore, ought to have been a high priority chapter in the series. It has, unfortunately been delayed while my attention has been occupied with other matters, and in the meantime I have allowed modern methods in astrometry to slip by me and I am not at all qualified to write an authoritative or detailed account of this important subject. However, from time to time correspondents have urged me to fill the gap in this series of topics in celestial mechanics. I shall respond not with an authoritative account of the detailed observing and reduction techniques, but rather with a few general remarks. These remarks will include a comparison of the new methods of CCD astrometry with the older photographic methods. While such a comparison may be of interest to some, the younger generation may be bewildered by it, for, to the modern CCD astrometrist, the CCD is not "new" technology at all; it is not only well established but it is the only technology they have ever known. Many have never handled photographic materials, and indeed photographic emulsions to them are part of the early history of astronomy. Nevertheless some comparison with the old and the new may be of interest.

When CCDs first came into use in astrometry, it was early evident that useful images could be obtained on a CCD far faster than on a photographic emulsion, that far fainter stars could be reached, and higher precision was obtainable. Initial misgivings were that the devices were small and covered only a small area of sky, so that only a few comparison stars were available. Available star catalogues contained positions of only a few hundred thousand stars. As time passed, catalogues were produced that contained many more stars, but there were still misgivings because the newer catalogues, while containing many more stars than the earlier traditional ones, were single-epoch catalogues lacking proper motion data. Against this objection it would be argued that the many faint stars in the newer catalogues were so distant that their proper motions were negligible. This was something of an act of faith, because it is by no means improbable that our Galaxy contains a large number of intrinsically faint stars that are relatively close to us and which may therefore have appreciable proper motions. A further misgiving was that CCDs were relatively insensitive to the blue end of the spectrum – the opposite situation from photographic emulsions, which were typically more sensitive to blue light than to red.

These early perceived drawbacks are now a thing of the past. Modern catalogues suitable for astrometry are available "on line", and contain billions of star positions, and even the initial lack of proper motions is being rapidly remedied.

Let us recall what was involved in obtaining usable astrometric positions of, for example, asteroids, in the photographic era, and compare the situation with the methods in common use today.

In what follows I describe the several steps involved in obtaining and measuring an astrometric position of an asteroid. Under each step I outline what was done (a) in the photographic days and (b) with modern CCD methods.

1. (a) First you had to obtain a photograph of the asteroid. (As Mrs Beeton would have written: "First catch your hare".) To do this would require an exposure of many minutes, or even an hour or even more. During this long exposure time, it was difficult – and tiring – to ensure that the telescope was tracking the stars accurately over such a long time. You could not just allow the telescope to be driven, unattended, by its sidereal drive, but the observer had to stay at the eyepiece for the whole duration of the exposure, constantly vigilant against any small departures from perfect tracking. Of course you would need a second photograph – because the asteroid could only be identified by its motion against the background of the fixed stars. Typically one would wait about an hour before taking the second photograph.

   During a long time exposure, an asteroid would often appear as a short streak, while the stars were (almost) point-like. For faint asteroids, for which an orbit and ephemeris were at least approximately known, a useful (though not particularly easy) technique would be to move the telescope not at the sidereal rate but to follow the predicted motion of the asteroid. That way, the asteroid image would build up, and would appear on the photograph as a point. Thus images of faint asteroid could be obtained. The stars images, of course, then appeared as streaks, and this then made it difficult to measure the streaked stellar images during subsequent analysis of the photograph.

   (b) Today, a CCD still has to be exposed, but exposures are typically just a very few minutes, and the interval between the first and second exposures are again typically measured in minutes. Indeed, because of the speed at which exposures are obtained and the small interval needed between exposures, it is almost universal practice to make at least three exposures in rapid succession, rather than just two with an hour between each.

   The corresponding technique for faint asteroids is to take a series (perhaps a dozen or more) of short exposures of the required field, keeping the telescope at sidereal rate. The several images can then be stacked electronically, either (according to choice) so that the stellar images are all stacked upon one another and the asteroid appears as a (barely visible) row of dots, or the several images can be offset before they are stacked, in such a manner that the several asteroid images are stacked upon each other to form an easily-visible pointlike image, and the stars appear as a row of dots. The asteroid position can then be easily measured relative to one of the pointlike stellar images, which remain perfectly usable for astrometric measurement (unlike the streaked stellar images in the photographic method).

2. (a) The photograph had to be developed. This not only meant "messing around" in the darkroom, but one had to wait for hours (after a long night of observing) while the film was first washed and then dried before one could start measurement.

(b) It is true that a CCD image doesn't have to be "developed" in the same sense that a photographic film had to be – but the CCD observer doesn't quite get off scot-free here. There is a certain amount of "image-processing" that has to be done, and this requires a not inconsiderable amount of experience and know-how. A beginner doing this for the first time may well find it difficult, bewildering and time-consuming. But, once the process has been learned, it becomes very quick and automatic – whereas the process of developing, fixing, washing and drying a photographic plate never gets any easier or faster.

3. (a) Any asteroids on the photograph have to be found. This was done using either a blink comparator or a stereocomparator. In the former the two photographs could be viewed – either through a microscope or projected on to a screen – one after the other in rapid succession. An asteroid would have moved its position relative to the stars between the two exposures, and its presence on the two photographs could be detected because the image of the asteroid would hop to and fro as first one photograph and then the other was viewed. In a stereocomparator, the two photographs would be viewed simultaneously through a stereo binocular microscope. An asteroid that had moved relative to the stars between the two exposures would appear to the eyes, because of a stereoscopic effect to stand up above the plane of the stellar images. These methods were exceedingly effective, but nevertheless a thorough search of a pair of photographs with either of these instruments was time-consuming and tiring.

(b) The blink technique is also used in CCD astrometry. As mentioned above, it is usual to obtain three images rather than two. The three images can be displayed, one after another in rapid succession, on a computer screen, and any asteroid image will be seen hopping across the screen and back over and over again. In a variation of this technique the three images are obtained through three coloured filters, perhaps red, green and blue. The three images are then stacked on top of each other on the screen, so that the star images appear white. A moving asteroid appears on the screen as three coloured dots (or short dashes) and can be seen very quickly. In yet another technique possible with CCD images, two exposures of a star field can be superimposed on the screen, one positive and the other negative. Thus one image is subtracted from the other, and the computer screen appears blank – except for an asteroid that has moved between exposures. The asteroid appears as two adjacent spots on the screen – one white and one black. Although any of these three techniques is far quicker and less tiring for the measurer than "blinking" or "stereoing" a pair of photographic films, they are by no means the last word in locating asteroid images on CCD exposures, for computer software is available that can detect any object that has moved between two exposures, and can indicate any such objects to the operator.

One problem with CCD images is that the occasionally faulty pixel on a CCD array can look like as asteroid image on the screen, and also it is common for several pixels to be hit by a cosmic ray particle during the exposure, and this also produces a blemish on the image which looks a bit like an asteroid. However any operator who has measured a few asteroid positions very soon gets to recognize the characteristic appearance of either a bad pixel or a cosmic ray hit, and to distinguish either of these on sight from a real asteroid image. Computer software that is also used to scan pairs of images to detect moving objects can also be programmed to recognize these blemishes, so that in practice they are no real problem to an experienced operator.

4 (a) When we have located an asteroid image on a photographic plate or film, we are not yet ready to start the actual measurement. We have to identify enough comparison stars on the photograph, and look up and write down their right ascensions, declinations and proper motions by comparison of the photographs with star charts and catalogues. This was always a laborious, tiring and time-consuming part of the procedure, and could occupy a couple of hours or so after a long night of observing and as the evening of the next night rapidly approached.

(b) In the CCD age, this formerly tiresome procedure is over in seconds. All that need be done is to click on the image as many stars as one would like to use as comparison stars. Not just half-a-dozen as in the photographic era, but two or three dozen if you like. The astrometric software in use has access to an enormous catalogue of billions of stars, and instantaneously reads their positions from the catalogue and marks each "clicked" star with a circle for the operator to see. The operator has no need to write down or even to see the positional data of his comparison stars.

5. (a) When we have, after a couple of hours or so, managed to identify the asteroid and the comparison stars on a film or plate, we are at last ready to start the measurement. The film is carefully positioned on the stage of a measuring microscope or "measuring engine" as it was called in the old days. Several settings of a microscope crosshair , in both the *x*- and the *y*-directions, were made on the asteroid and the comparison stars. After each setting, a reading of the position was made on a vernier scale that was part of the measuring engine and was duly recorded with pencil and paper. After the asteroid and all the stars had been measured, the film had to be reversed in the measuring engine, and all measurements repeated, in order to allow for systematic measuring errors. The process was very laborious and took several hours for every photograph. In the latter days shortly before CCD astrometry took over, we introduced some quite effective labour-saving devices. We directed a laser beam at a corner reflector attached to the movable microscope stage. The reflected laser beam was interfered with the incident beam to form a system of standing light waves. As the microscope stage moved, a phototransistor counted the number of half-waves, and hence it recorded the position of the microscope stage to a precision, in principle, of half a wavelength. As each setting was made, the position of the microscope stage was sent automatically to the computer that was to be used subsequently to perform the necessary calculations. Apart from greatly increasing the precision of the measurements, the measurer did not have to read a vernier scale, nor even did he have to write down the position. While this device greatly increased the efficiency of the operation, nevertheless several hours were still needed to measure each photograph.

(b) So how does one measure the positions of the asteroid and the very numerous comparison stars on a CCD? How tedious is the measurement? The astonishing answer is that there is no measurement to be made! The measuring process is bypassed entirely! The reason is that the image of every star sits already on a certain pixel, and all that has to be done is for the computer to read which row and which column that pixel is on. As soon as the exposure is made, the position is already determined! In fact, the situation is even better than that. As described, the positional precision of the measurement is determined by the pixel size. If the pixel measures one arc second by one arcsecond at the focal plane of the telescope, then the precision of the measurement, as we have described it, will be no better than one arcsecond. But this is not the case at all. In practice, a stellar image is spread out over several pixels in two dimensions, each of several pixels holding a certain number of photons. (Not literally photons, of course, but electron-hole pairs, each of which has been generated by a single photon.) The software reads the number of photons in each of the pixels over which the stellar image is distributed, it fits a statistical distribution function (such as a two-dimensional gaussian function) to the image, and calculates the "centre of gravity" of the image to a position of typically about a tenth of a pixel. And so, as soon as the exposure is made, we have the position of the asteroid and of dozens of comparison stars already determined for us to a tenth of an arcsecond or better. Furthermore, the right ascensions and declinations of the comparison stars used are automatically read from an on-line star catalogue, and the calculations to determine the right ascension of the asteroid (or, more probably, of several asteroids recorded on the CCD) are instantaneously computed.

Since all of these calculations can be done instantly by any of several available computer packages, they can be done by anyone with little mathematical training. This has obvious advantages, though the availability of "do-it-yourself" computer packages to the untrained or the unwary may also have some drawbacks. For example, does a given astrometric computer package include such corrections as differential refraction and aberration, proper motion, and so on? Perhaps some do, and some don't. How can one tell – or how can a nonmathematically-trained user determine what corrections are included in the package? For the experienced professional scientist, this may not be a problem, but there are pitfalls to be wary of when a prepackaged program is in the hands of an untrained user, who just wants the "answer" as quickly as possible, without necessarily wanting to know how that answer is obtained.