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Nick James explained the secrets of the mysterious art of astrometry

An introduction to astrometry

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Introduction

To determine the orbit of an asteroid or any other solar system body we need to measure its position on the sky very accurately. Usually we need at least three well-spaced *astrometric* positions before we can compute the orbit. Astrometry is the process of making these accurate measurements at a given time. Good amateur astrometry has errors of less than one arcsecond in each coordinate, and an accuracy of 0.3 arcseconds is achievable with common amateur equipment and careful observation. This corresponds to the apparent diameter of a 10p piece placed almost 10 miles away!

In this short introduction I will concentrate on the astrometry of asteroids, but similar techniques can be applied to comets and many other astronomical objects.

The astrometric process

The basic technique is to acquire an image with an exposure which is just long enough to obtain a good record of the asteroid. If the exposure is too long the image will be trailed and this can cause problems during the measurement. If the exposure is too short the image will be weak and the accuracy of the measurement will suffer. The UTC times of the start and end of the exposure must be recorded to an accuracy of at least one second. The position of the asteroid is then obtained by measuring its X–Y coordinates on the image along with the coordinates of a number of *reference stars*. These stars are selected so that they have accurately known positions taken from an astrometric catalogue, and they can be used to determine what are known as the *plate constants* of the system. These constants define how the X–Y coordinates of objects in the image relate to real RA and Dec positions on the sky and so they can be used, along with the measured coordinates, to determine the asteroid's position.

Up to around twenty years ago astrometric catalogues were sparse and so very wide fields were required to ensure that the asteroid and a few catalogue stars could be recorded on the same image. The recording medium was usually a large photographic plate, and the X–Y coordinates of the asteroid and stars were measured using a measuring engine. Measuring engines ranged in size from small, home-made, table-top devices to huge beasts that required an entire room to themselves. In all cases the objective was to measure the linear position of an object on the film or plate to an accuracy of a few thousandths of a millimetre. The observer would carefully measure the positions of the reference stars and the asteroid using a microscope eyepiece and would then extract the star positions from a printed catalogue. The results would then be reduced to get the actual RA and Dec position of the object.

This process was painfully slow and complicated and only a very few observers had the necessary skills to do it accurately. I can remember trying this once during a visit to Denis Buczynski's observatory at Conder Brow in the late 1980s. The reduction of a single image took up an entire morning and by the end of the process I had all but lost the will to live.

In the early 1990s two things happened that dramatically changed the way astrometry was performed. At around this time CCD cameras started to appear in the amateur community. CCD chips are ideal for astrometry since they consist of a regular array of pixels which provide a very accurate reference grid. Furthermore computer programs can automatically extract the X–Y coordinates of objects to an accuracy of a small fraction of a pixel. This immediately eliminated the arduous job of measuring each star using a mechanical measuring engine. The second development was the availability of star catalogues containing a far denser grid of stars. This meant that the small field of CCDs was no longer a barrier to performing astrometry. In 1992 the Hubble Guide Star Catalogue (GSC) was released on CD-ROM. This contained reasonably accurate positions for stars down to 16th magnitude and so plenty of reference stars were available even in narrow fields. From that time onwards astrometry became a straightforward process and these days computer tools exist which automate the entire reduction.

What equipment do I need?

Any instrument which can take CCD images at reasonably high resolution and which can reach the required magnitude will be suitable for this work. If possible the field of view should be greater than 10 arcminutes or so to ensure adequate catalogue stars, and the pixel resolution should be no less than 2 arcseconds for best results. The software can usually resolve positions down to about one tenth of a pixel and so 2 arcsecond pixels lead to measurement errors of around 0.2 arcseconds.

It is important to ensure that the clock on the PC that you are using for image acquisition is accurate. Main-belt asteroids move at around 40 arcsec/hr so our target accuracy of 0.3 arcsec corre-

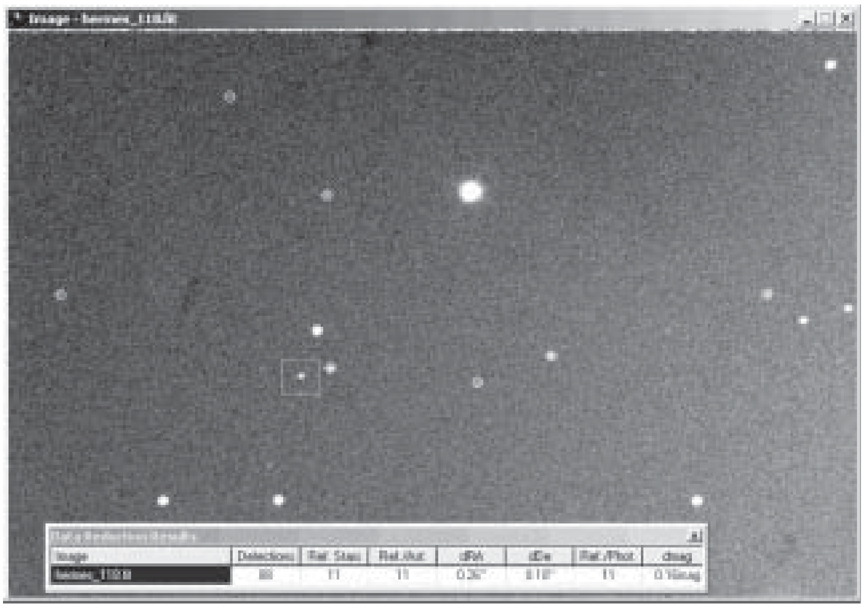

Figure 1. A screenshot showing an image of asteroid 1937UB (Hermes) being reduced using *Astrometrica*. The circled stars have been identified and correlated with stars in the USNO-A2.0 catalogue. A total of 11 stars are used in the reduction and these have RMS position errors of 0".26 in RA and 0".18 in Dec. Hermes is the object in the box.

sponds to a time error of around 30 seconds. NEO asteroids move much faster. At 1 deg/hr a one second error in the exposure time corresponds to 1 arcsec! The recorded exposure time should always be mid-exposure, taking account of shutter open/close times. PC clocks are notoriously unreliable and drifts of 30 seconds a day are common, so you should make sure that you set your PC's clock accurately before starting an observing session and check it again afterwards. This is particularly important if the software that you use to acquire CCD images stops the PC's clock during downloads. If your PC is connected to the Internet the best solution is to arrange for your PC to be automatically synchronised to UTC using a network time server. The Network Time Protocol (**http://www.ntp.org**) can keep your computer synchronised to within a few milliseconds of true UTC.

One note concerning manual setting using GPS: beware that some handheld GPS receivers, while they may know the time very accurately, often display it as a low-priority task. The displayed time can be up to a second or two slow.

What are the best catalogues to use?

The Guide Star Catalogue made CCD astrometry possible. It came on two CDs with 19 million objects to magnitude 16, but it was not particularly accurate and many better catalogues are now available. The USNO A2.0 catalogue contains over 500 million stars with good quality positions but no proper motions. It requires 11 CDs (or two DVDs) and it is probably the easiest catalogue to use with current software.

Since the USNO-A2.0 is so large, a subset was produced specifically for astrometry. The USNO SA2.0 contains 50 million stars between magnitudes 16 and 19 selected so as to provide a uniform distribution on the sky, and it fits on a single CD. I find that it is more difficult to use this subset catalogue when reducing most fields and I would recommend that you go to the additional effort to obtain the A2.0 if possible. Both catalogues are available via FTP from: **ftp.nofs.navy.mil.**

Recently, a new catalogue, the USNO B1.0 has been released. This contains over a billion stars to 19th magnitude and it includes proper motions. The size of this catalogue is approximately 70GB (15 DVDs) but it is only available online at the moment (**http://vizier.u-strasbg.fr/**) and this makes its use rather less convenient than having the catalogue on your local computer.

It is the recommendation of the Minor Planet Center that observers who are still using the GSC as their reference catalogue should migrate to the USNO-SA2.0 (or -A2.0), unless their field of view is large enough to contain sufficient USNO CCD Astrograph Catalog (UCAC 1) stars, in which case they should use the original form of this latter catalogue.

What software should I use?

Once you have the images there are a number of astronomical image processing programs which can perform the astrometric reduction with the minimum of manual intervention. One of the best is Herbert Raab's *Astrometrica* (**http://www.astrometrica.at**). This program can be downloaded and used for 90 days without having to register it. The registration cost is a very reasonable €25 (~£17).

An example reduction using *Astrometrica* is shown in Figure 1. The software completely automates the process by first detecting all of the stars in the image and then comparing them against the selected catalogue. In order for it to do this you need to tell it the approximate scale and orientation of the image along with approximate centre coordinates. *Astrometrica* uses a centroiding algorithm which is used to obtain the X–Y centres (centroids) of each object to a fraction of a pixel, and the stars which correspond to catalogue objects are then used to determine the plate constants of the image. A computer is very good at determining the centroid of objects since it uses exactly the same algorithm on every

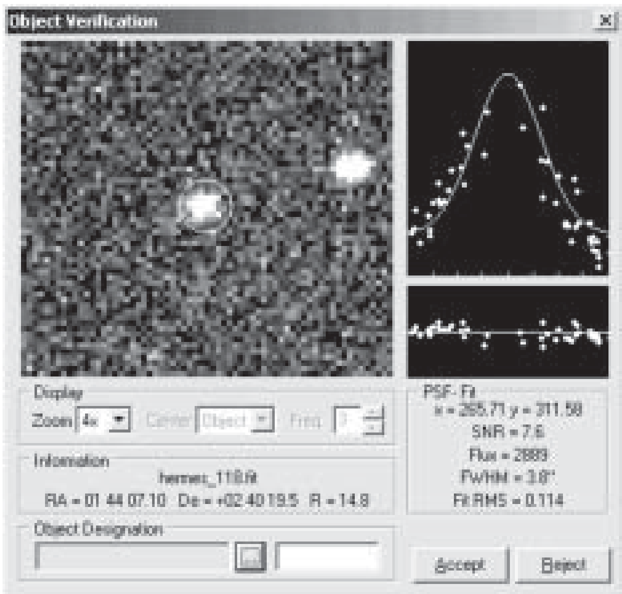

Figure 2. A screenshot of the panel produced by *Astrometrica* when you click on a target object. The program fits the object's profile to a Gaussian curve and determines the X–Y coordinates of the centroid. These are then converted to RA and Dec.

object. This is particularly important where images are slightly trailed due to guiding errors. The computer, unlike a human observer, will consistently choose the centroid at the same point so that the errors are minimised.

Once it has the plate constants *Astrometrica* is ready to perform astrometry on any object in the field. This is as simple as moving the mouse cursor over the object and clicking. The program computes the centroid of the object and converts it directly to RA and Dec (Figure 2).

Most recent computers have hard disk storage capacities in excess of 100GB so it is quite practical to store the entire USNO-A2.0 catalogue on the local disk. This has the advantage that all the information that *Astrometrica* requires is available without any manual intervention. I have done this and the automatic reduction of a frame now takes no more than a few minutes. A far cry from the entire morning it took me to do a reduction from a photographic plate using the old methods!

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COD 970
NET USNO-A2.0
ACK MPCReport file updated 2003.10.15 21:20:20

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      J37U00B  C2003 10 15.83578 01 44 06.90 +02 40 18.9   14.5 R   970
      J37U00B  C2003 10 15.84005 01 44 06.16 +02 40 16.7   14.6 R   970
      J37U00B  C2003 10 15.84432 01 44 05.44 +02 40 14.2   14.5 R   970
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Figure 3. This is the standard MPC report format. The first column identifies the object (in this case asteroid 1937UB Hermes). The next three columns are the time of mid-exposure in year, month, day format. The next six columns are the measured position in RA and Dec. Finally the estimated magnitude (14.6), photometric band (R) and station code (970) are given.

What should I observe?

If you are new to astrometry I would suggest that you start by measuring some of the brighter main-belt asteroids and submit your results to the undersigned for checking. There isn't much science in this but it will help you check your system against well-known objects. When you are happy with your accuracy you can move on to more challenging targets.

One of the most important areas is to make follow-up astrometric observations of newly-discovered Near Earth Objects (NEOs). These can be challenging since the brightest objects are usually around magnitude 17 but the data obtained is very useful. The Minor Planet Center (MPC) maintains an excellent resource on their NEO confirmation page: **http://cfa-www.harvard.edu/iau/NEO/TheNEOPage.html.**

Another area where astrometry is critical is in the improvement of minor planet occultation predictions. See the website at **http://mpocc.astro.cz/** for more details.

How do I report my observations?

In order to use your astrometry the analyst also requires knowledge of your position on the Earth, accurate to a few tens of metres. You can obtain this information using a GPS receiver or large scale maps. If you submit regular astrometry you will be allocated an observatory code (mine is station 970) so that you don't need to repeat this information each time you submit observations.

Observations should be submitted in the standard format recommended by the Minor Planet Center. An example of this format is shown in Figure 3. Most software will produce data in this format and *Astrometrica* will even e-mail it for you. More details of the report format can be found at **http://cfa-www.harvard.edu/iau/info/Astrometry.html.**

You must make sure that any e-mails containing astrometric data are sent as plain text. Do not use HTML, MIME, Word files or any other format. The commonly used Outlook Express e-mail client sends HTML mail as default. Switch this off as follows:

Click on Tools/Options/Send

Then tick the box 'Plain Text' under 'Mail sending format'.

Conclusions

Astrometry used to be a very demanding activity and this was reflected in the small number of amateurs who submitted results. With the advent of CCDs, computers and excellent on-line catalogues, basic astrometry is now straightforward and the careful observer can produce excellent results with the minimum of effort.

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