HIGH DENSITY REQUIREMENTS

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1. Specification and Significance

I will consider here some practical astrometric requirements, from the perspective of an optical astronomer working on objects much fainter than the limits of the primary catalogues, i.e., from 15 mag down to 20 mag and fainter. I take 'high density' to mean surface densities of order 100 or more stars per square degree; these two criteria are roughly equivalent (Bahcall & Soneira, 1980). The positions of such objects are routinely available to an accuracy of around 0.5–1.0 arcsec, e.g. from various digitised versions of the Schmidt Telescope photographic sky surveys. However, these sky surveys themselves readily yield *internal* accuracies at the 0.1 arcsec level, as demonstrated by repeated measures of the same plates. The problem is that the discrepancies can be ten times larger than this when different machines or plates are used, when a wide magnitude range is covered, when relative positions are compared over distances of a degree or more, or when absolute positions are needed for comparison with, say, radio catalogues. The challenge now is to improve this accuracy; we should to be able to specify the absolute positions of all well-defined optical objects to better than 250 mas, anywhere in the sky, at any epoch and regardless of magnitude or colour.

1.1. CONNECTING THE REFERENCE FRAMES

A basic problem is that the although reference frame for bright stars, down to $\sim$ 11 mag, is now very well-defined, thanks to Hipparcos and Tycho, it is difficult to connect fainter optical images to this frame. The images on deep sky survey photographs, such as those taken on the Oschin, ESO and UK Schmidt (UKST) telescopes, begin to develop diffraction spikes and other complex structure for stars brighter than $\sim$ 15 mag. Thus there is a problem in relating the astrometry for faint target stars to the bright reference stars; systematic errors arise at the level of several tenths of an arcsec, and since these depend on the detailed shapes of the outer parts of bright star images, they vary across plates, from plate to plate and from machine to machine.

1.2. SUPERNOVA 1987A

A good example of the current situation is afforded by SN 1987A. The early images from the Hubble Space Telescope showed that the supernova was surrounded by a spectacular ring of material about 1 arcsec in diameter, ejected by the progenitor star at an earlier stage of its life. When the supernova reappeared as a radio source in 1990, the first radio maps indicated that the centroid of the emission was located about 0.5 arcsec north of the supernova (Staveley-Smith et al., 1992). Did this mean that the radio emission was coming from part of the pre-supernova ring, or was it really coming from the central supernova remnant? Clearly these were two completely different possibilities, with very different astrophysical implications and explanations. The situation was only resolved after a special campaign to improve the registration of the optical and radio reference frames in this particular direction, using pre-release data from Hipparcos, specially-measured photographic plates and two radio reference stars (Reynolds et al., 1995); this enabled the images to be registered to $\sim$ 70 mas and showed clearly that the radio emission was centred on the supernova, and that the peak radio brightness lay inside the ring, as expected if the emission arises from the expanding ejecta.

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1.3. MULTI-OBJECT WIDE-FIELD SPECTROSCOPY

Different problems arise in the case of multi-object spectroscopy, as with the new Two-degree Field (2dF) instrument on the Anglo-Australian Telescope (e.g., Cannon, 1997). Here the requirement is to produce positions for 400 faint target objects (magnitude ≥ 18) to a relative accuracy better than 0.25 arcsec across 2°, and to relate these to a few brighter guide stars at $B \sim 15$. At present, errors at the 0.5 arcsec level are not uncommon, leading to significant loss of light with the 2 arcsec diameter optical fibres used in 2dF. There is a one-off need to determine the geometry of the 2dF optics and robot positioner, which requires a few dense sets of reference stars accurate to ~ 100 mas. For the guide stars, the main current problem is proper motions; in the past, errors at the 0.7 arcsec level have not been uncommon, although this should be solved soon when the UKST Second Epoch Survey is completed and fully digitised. The third problem is to map the Schmidt sky survey photographs well enough, especially the non-linear distortions near the plate corners, so that relative astrometry accurate to 150 mas can be achieved routinely, anywhere on the sky.

2. Sources of error

Several separate effects combine to produce the errors in positions derived from Schmidt photographs. Three produce large-scale distortions across the field: the optical characteristics of the *telescope itself, including its achromatic corrector and coloured glass filters*; *non-linear distortions* arising from the elastic deformation of the flat glass photographic plates, needed to fit the convex spherical shape of the focal surface; and differential atmospheric refraction. Atmospheric refraction itself involves at least three further separate effects: a large-scale distortion across the field which depends on zenith distance and azimuth; a differential effect for long exposures, due to changes in the above parameters and which also depends on the precise location of the guide star used (see Wallace & Tritton, 1979); and chromatic effects, since each star image is in effect an extremely low dispersion spectrum.

All of these effects are convolved in forming the actual star images, whose structure varies across the field. Additional asymmetrical effects arise from the diffraction spikes caused by the plate holder supports inside the telescope, and from internal reflections arising in the corrector lens (which are generally axially symmetrical, although they suffer vignetting near the edges of the field) and also in the filter, which are eccentric since the flat glass filters are not parallel to the curved photographic plate (see UKST Handbook, 1983, for a full description with illustrations). In addition to all of the above, there can be systematic errors in image shape due to tracking errors or wind shake.

Thus the structure of Schmidt telescope images varies with position in the field, with magnitude and with colour, and every plate is different since 'seeing', tracking, zenith distance and exposure time are all variable. In principle many of these effects could either be modelled or removed empirically, but in practice the photographic detector introduces further problems since it has limited dynamic range, so that the central regions of bright star images become saturated, and it is intrinsically non-linear. These last two factors mean that information has been lost and they limit the extent to which the data can ever be recovered from a single given plate.

Since the image shapes are very complex, especially for bright stars, the positions determined will also depend on the characteristics of each measuring machine (the effective size and shape of the pixel) and on the algorithm used to determine image position (centroid, equal intensity contours or whatever).

One further error can be introduced if incorrect reference star positions are used to reduce the data. Forcing the digitised data to fit erroneous positions will lead to distortions of the coordinate frame, especially if only a small number of reference stars are used.

The result of several of the above effects is to produce large scale 'swirling' patterns in the positional errors on Schmidt plates. These were first derived by the HST Guide Star group (Taff, Lattanzi & Bucciarelli, 1990) and have subsequently been found by other groups (e.g. Irwin, 1994). The patterns are revealed when data for a very large number of fields are combined, and appear to be constant for a given combination of telescope, plateholder and measuring machine, so that they can be corrected by using an empirical template or look-up table.

That these effects are partially due to vignetting of the out-of-focus filter ghosts of bright star images has been demonstrated convincingly by Morrison et al. (1996), in the case of the UKST(J) survey. They find a strong coma-like term when positions of stars in successive magnitude ranges are compared (using the old Astrographic Catalogue positions as a reference frame, and again combining the data for large numbers of plates); the effect starts suddenly at a radius of 2.7° and increases rapidly with radial distance thereafter, following the known pattern of vignetting in the UKST.

3. Cures

Since the astrometric errors increase rapidly towards the edges of Schmidt fields are strongly magnitude-dependent for over-exposed bright stars, and often include significant proper motion terms, there is one obvious quick solution for specific projects requiring accurate astrometry: obtain a new, short-exposure Schmidt plate, centred on the field of interest. This is not however a suitable long-term strategy, since (a) the big Schmidts are expensive to run and may not even be taking plates within a few more years, and (b) the data do already exist on the various all-sky surveys, provided we have sufficient knowledge and adequate tools to extract the information.

It seems that the largest current sources of error arise in tying the deep survey photographs, with good stellar images in the range $15 < B < 20$, to bright (~ 10 mag) reference stars with badly over-exposed images. Thus a global cure could be effected with a special astrometric survey, designed to bridge the gap from 10 mag to 15 mag. Such a survey could either be done using short-exposure Schmidt plates (but not films), or as a separate exercise using an astrographic camera or transit circle equipped with CCDs. All three possibilities are currently under discussion by various groups; although in principle any one of the three should be adequate to solve the problem, it is highly desirable that at least two of them are carried forward, both to validate the data and because of the long-term funding uncertainties currently affecting most such projects. In due course, the identification of faint radio galaxies and quasars should provide a consistency check, to verify that the bright and faint optical reference frames have been properly connected.

An alternative 'internal' approach would be to use detailed pixel maps of many stellar images and fit them to a standard profile for each plate, after allowing for all known instrumental effects. This would however require more computer power, and better understanding of the image structure than is available today.

So far as the UKST is concerned, a pilot study is underway to check that a Short Astrometric Survey (SAS) would be both necessary and sufficient to solve the problem. There are already indications that this is true: comparison of many deep UKST plates of the same field shows that the scatter in residuals is small for stars at all magnitudes, so that a given exposure is repeatable and hence in principle correctable (Hawkins, private communication), while the large systematic errors seen for bright images on deep plates decrease rapidly with increasing magnitude (Morrison, private communication) and are much smaller on short-exposure plates (Monet, private communication).

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