ASTRONOMY FROM WIDE-FIELD IMAGING

Part Five:

IMAGE DETECTION, CATALOGUING AND CLASSIFICATION

IMAGE DETECTION, CHARACTERIZATION AND CLASSIFICATION, AND THE FUTURE ROLE OF CCDs IN WIDE-FIELD ASTROMETRY

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1. Image Detection, Characterization and Classification

1.1 THE SURVEYS

The extraction and characterisation of information from photographic emulsions is the subject of this review. Since the major Schmidt Telescope full sky surveys form the bulk of the photographic emulsions currently under intensive study, I will limit my remarks to them, although most would be applicable to any of the emulsions now in use. A listing of the major direct imaging surveys is given in the article by van Altena et al (1993).

1.2 LIMITS DUE TO SIGNAL-TO-NOISE CONSIDERATIONS

Table 1 lists the various digitization projects recently completed, or in the process of being done. From the standpoint of noise and information content, there are essentially three classes of emulsions listed in Table 1: the high speed coarse-grained 103a-; the medium-grained IIa-; and the fine-grained IIIa- and IV-N. Although the IIIa and IV emulsions are slightly different, not too much error will be made if we assume that they are essentially the same. The various surveys have been separated in Table 1 so that similar emulsion types are listed on the same line along with an estimate of the average density of the sky background. There are significant variations in the actual sky background on individual plates so the listed values should be taken as a rough guide. The density noise in a 1000 square micron area has been taken from the work of Latham (1978), Furenlid, Schoening & Carder (1977), and unpublished work at Yale. In order to estimate the reliability of detection and classification near the plate limit, we have assumed a signal 0.5 mag above the sky and then estimated the contrast for each emulsion at the appropriate density from data supplied by Eastman Kodak (1987). It is then possible to calculate the 'Signal/Noise' for such a signal, where we define the S/N as the ratio of the signal above the sky to the noise within one pixel, where the noise has been scaled from the value listed for 1000 square microns. What we see from this estimate of the S/N, is that for objects about 0.5 mag above the sky, the information in a typical galaxy image occupying an area of a few square arc-seconds will yield an overall S/N of about 10 to 25 depending on the emulsion. Depending on how the classification is parameterized, the certainty of the classification will vary, but ultimately the

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precision will be limited by the available S/N and that should be kept in mind while pushing the classification limit closer to the sky background.

Table 1. Digitization of Schmidt plates

Site	Surveys	Pixel size		Emulsion	Dsky	N(1000)	S/N (0.5m)
STScI	POSS-I	1.7"	25 µm	103a	0.6	0.039	2.7
	Pal Quick V	1.7"	25 µm	IIa	0.4	0.025	2.4
	SERC-J	1.7"	25 µm	IIIa	1.0	0.025	7.8
	POSS-II	1.0"	15 µm	IIIa, IV	1.0	0.025	4.7
ROE	ESO-B	1.1"	16 µm	IIa	0.6	0.032	1.3
	POSS-II, SERC-J, SES-R	1.1"	16 µm	IIIa, IV	1.0	0.025	5.0
Camb.	POSS-I	0.5"	8 µm	103a	0.6	0.039	0.9
	SERC-J	0.5"	8 µm	IIIa	1.0	0.025	2.5
Minn.	POSS-I, Luyten	0.5"	8 µm	103a	0.6	0.039	0.9
	POSS-II	0.5"	8 µm	IIIa, IV	1.0	0.025	2.5
USNO	POSS-I	0.9"	13 µm	103a	0.6	0.039	1.4
	USNO QJ	0.9"	13 µm	IIIa	0.2	0.010	1.8
	POSS-II	0.9"	13 µm	IIIa,IV	1.0	0.025	4.1

Explanation of the columns:
The above table summarizes the digitization of Schmidt plates. The columns list information for each 'Digitization Center' giving an acronym for the center (**Site**), the **Surveys** being digitized, the digitization **pixel** size in arc seconds followed by the size in microns, the **emulsion** used, the average density of the sky background, (**Dsky**), the density noise at the sky for an area of 1000 square microns, **N(1000)**, and the approximate signal to noise for an object in one pixel that is 0.5 mag above the sky, **S/N(0.5m)**.

1.3 SKY BACKGROUND VARIATIONS

The sky background varies across each plate due to variations in the emulsion sensitivity, irregularities in the development process, optical problems such as vignetting, and disturbances due to the presence of bright stars, large galaxies and nebulae. Since it is important to maintain a uniform limiting magnitude even in the presence of a non-uniform background, each of the digitizing groups has developed some kind of background follower to dynamically follow the background at each location on the plate, or else they utilize a coarse prescan and model to interpolate for the position under study. Generally some variation on determining the mode of the local distribution of density values or a median filter is used and then an interpolation is done between the points. These procedures work well, except when close to a bright star (see for example Fig. 1 in Beard et al. 1990) and then manual intervention may be required to correct the background.

1.4 PIXEL EXTRACTION

Two extremes currently exist for retention of pixel data, from the complete archiving of plate scans as done at the Space Telescope Science Institute, see for example Lasker et al. (1990), to the retention of the pixel coordinates at selected density thresholds as done by the Minnesota group, see for example Pennington et al. (1993). However, even in the case where all of the scan data is archived, the software parameterization of the image characteristics selects data defined between certain threshold limits. The limiting magnitude is defined by thresholds set in hardware or software, since too low a threshold will swamp the system with false images, while a high threshold may miss the faintest images. The threshold adopted for the ROE/COSMOS extraction routines is 7% above the local sky background (Beard et al 1990; Weir & Picard 1992), which for the IIIa emulsions corresponds to S/N = 1.4 per pixel. If the background noise is distributed normally, then eight false *positive* detections should be obtained among 100 pixels, i.e. in a 10 x 10 raster. It is therefore important to understand the transition between the intrinsic noise of the emulsion discussed earlier and real images. Most algorithms require some sort of connectivity between pixels with densities above a threshold before accepting a detection, see for example Thanisch et al. (1984), or other approaches are used, such as the Wavelet method of Bijaoui (1993). In those ways the impact of noise in a pixel is reduced so that faint images can be detected, however the requirement for a large number of connected pixels above a preset threshold will naturally discriminate against small faint images.

1.5 IMAGE CHARACTERIZATION

Single isolated images can be characterized by their position, edge gradients, skewness, ellipticity of the isocontours and magnitude. The situation becomes considerably more complicated for blended images, which will be dealt with in the following section. Depending on the characteristics of the measuring machine and the type of data provided, differing strategies for characterizing an image can be adopted. In the most general case where all of the pixel data has been extracted it is possible to model the image in a detailed way by fitting a point spread function (psf) to the data, as done in the DAPHOT routines developed by Stetson (1987). Simplified approaches are used primarily for the purpose of increasing the throughput of the measuring machine/data analysis system, as for example with the Automated Plate Scanner (Pennington et al. 1993), where only the ingress and egress coordinates of an image are captured at specified isotransmission contours, or the system devised by Ortiz Gil et al. (1993) which is designed to work with rather small computers. In the latter case it is important to distinguish between plate flaws and stars, but careful separation of stars from galaxies is not important, while for the other systems star/galaxy separation is of critical importance. Based on the general agreement of the results obtained from the different systems it is apparent that the characterization problem can be solved adequately in many ways for Schmidt type images. The most precise characterization will be obtained with functional/psf fits to a full image scan, but the extremely steep image gradients and high contrast of the class IIIa- and IV emulsions require a pixel size that is impractically small given the plate size and corresponding file size for a full plate scan. If we accept that limitation, then most of the approaches appear to yield satisfactory and similar results for the characterization of images.

1.6 BLEND RESOLUTION

Blend resolution is a major problem for all of the surveys. Algorithms have been developed by Stetson (1987) who searches for multiple peaks within an image and then attempts to fit multiple psfs at those peak positions. Jarvis & Tyson (1981) search for saddle points along the major axis of an elongated image, divide it into two images and proceed iteratively to subdivide the image. Humphreys et al (1987) use an isophotal approach, as does Irwin (1985) to subdivide the image. Beard et al. (1990) discuss the COSMOS algorithm which is a variation on the isophotal method for separation of images.

I believe that while all of the algorithms work effectively for high signal-to-noise images at, say, the 15th to 17th magnitude range for the large Schmidt telescopes, there are major problems for both fainter and brighter images, primarily due to low S/N situations. When the signal is low, then the probability that an apparent bifurcation in the image is due to multiplicity decreases dramatically. When the signal is high, the noise increases (see for example Furenlid et al. 1977) and false multiplicity is the rule rather than the exception. The latter is especially true for Schmidt telescopes where the psf for bright stars varies over the plate due to internal reflections between the emulsion and the filter and the interference of the diffraction pattern due to the plate holder support system. Any user who has examined the Schmidt survey catalogues at the edges of the plates will come to the conclusion that the problem of blend resolution still has a long way to go. I believe that the major improvements will come with the use of a realistic psf that varies over the field-of-view, with magnitude, and incorporates in a more or less rigorous way, the limitations imposed by S/N in the image. Lanteri et al. (1993) are studying the problem of image simulation for Schmidt telescopes so we might be able to improve the problems for both blend resolution and astrometry and photometry in the future.

1.7 PHOTOMETRY

Three major problems exist with the extraction of photometry from Schmidt telescope plates: first, the variation of the zero-point of the photometric system over the field-of-view; second, the variation of the psf over the field-of-view and with magnitude; and third, the lack of photometric standards. The photometric zero-point varies over the field due to emulsion coating inhomogeneities, developing non-uniformities and vignetting in the telescope, which is a function of the various obscurations in the field-of-view. The cause of psf variation with field angle and magnitude were discussed in the previous section. The situation with photometric standards is improving due to the CCD photometric observing programs at the STScI and different observatories, which will provide deeper standards, but still only at one, or a few, field positions. Various techniques have been developed which overcome some of the problems due to the varying zero-point, but a simple comparison of the derived photometry in the overlapping parts of the Schmidt plates demonstrates that it is not a complete solution to the problem. Probably the only adequate solution to the photometric problem will be the use of extensive drift scan CCD photometry which will yield enormous numbers of ‘photometric standards’ covering the whole plate to establish both the scale and zero-points of the photometric response of the emulsion.

A different problem is encountered in determining the magnitudes of stars versus those of galaxies. Since the ‘psf’ for a galaxy is different from that of a star, the algorithm used must differ and it is therefore necessary to know whether the object is a star or a galaxy. Derived magnitude differences of several magnitudes for the same object can occur between the different surveys when in one case it is classified as a galaxy and in the other a star. The fact that such differences exist demonstrates the inadequacy of the current star/galaxy discriminators, in spite of the fact that more investigators claim 97% or better reliability in the separation. While this will probably be a point of contention, I believe that the ‘training sets’ of images used to develop the classifiers may not be representative of the whole data set.

1.8 ASTROMETRY

For the Schmidt Survey case of 'astrometrically undersampled' images that are produced by the existing measuring machines, the astrometric precision of the derived x, y coordinates are similar for well-exposed, but not too saturated images. Given the degree of undersampling, the precision of the centers is probably slightly better for the methods that use psf or functional fits to the two-dimensional data than those that rely on the centroiding of contours, or moments of the data. On the other hand, the accuracy of the derived equatorial coordinates is completely dominated by systematic errors in the models adopted for transforming the x, y coordinates into equatorial coordinates. While S/N considerations for well-sampled images should yield image centers with a precision of 0.2 µm or 0.013" (see for example Lee & van Altena 1983), the best local precision that we have found from comparisons with our astrograph plates is about 0.10" or 1.5 µm and more typically 0.25" or 3.7 µm. However, positional errors of 1" (15µm) are not uncommon, and near the plate edges errors of 10" (150 µm) are sometimes found. The value for the typical local precision (1.5 µm) is consistent with the accuracy of the high speed measuring machines that produce the data, but the transformation modelling errors are often several times that value and faulty blend resolution problems no doubt account for the largest errors.

A solution to the modelling problem has been proposed by Taff et al. (1991). The 'Subplate' approach is a network of overlapping smaller regions, each using a simplified transformation. Continuity between the smaller regions is maintained by enforcing a considerable overlap of the sub-plates. The procedure is being applied (Bucciarelli et al. 1993) to the HST Guide Star Catalogue and will be issued on a new CD-ROM in the near future.

I should note, that no evidence has been produced to show that all Schmidt telescopes are affected by these modelling errors, in fact, the many proper motion investigations done with the Tautenburg Schmidt Telescope clearly demonstrate that there are no such problems over its smaller field-of-view. Probably, its longer focal length and smaller field of view require less bending of the plate and that in turn makes it easier for the emulsion to conform to the correct focal surface.

1.9 OBJECT CLASSIFICATION

The last subject in this discussion will be the classification of objects into stars and galaxies, which is reviewed in detail by Murtagh (1993) in the proceedings of this Symposium. The first approach utilizes the knowledge that star images are defined by the psf of the telescope, while galaxies are objects that have a resolvable shape, hence we need only draw the line between unresolved and resolved images. The separation is complicated because of variations in the psf with position in the field-of-view and with magnitude. In addition the observed image profile becomes poorly defined at faint magnitudes as the S/N decreases. The COSMOS classifier as described by Beard et al. (1990) examines the distribution of images in various parameter domains such as the peak density of the image versus the radius of the image and defines a stellar region in the diagram. This procedure is also done for domains involving the image gradient, average density in the image, etc., and then the results from the several domains are weighed to yield a star/galaxy decision. A minor variation on this method avoids making a yes/no decision and assigns a probability that the object is a star and then the joint probability of all the domains is computed at the end. The COSMOS algorithm and its variations are used not only for data from the COSMOS machine, but also as the classifier for the HST Guide Star Catalogue, (Lasker et al. 1990). The alternative is to create a set of templates for the different types of objects that are encountered on the plates and look for the best match to the object in question. This FOCAS approach was developed by Valdes (1982) and Jarvis & Tyson (1989) and has been used successfully by several groups including Weir & Picard (1992). The Neural Network approach, described by Odewahn et al. (1992) is similar in concept to FOCAS except that it uses an intelligent classifier which is trained on a set of objects that have been previously classified. A balance has to be struck on the size of the training set and the duration of the training, since excessive training leads only to a memorization of the set.

All of the classifiers are claimed to be accurate in the 90 to 97% range and in some cases even higher for well exposed images. The situation deteriorates rapidly as the plate limit is approached and the S/N drops. At that point various authors claim superior classification ability in the presence of noise for their algorithms, however our experience with two catalogues using similar classifiers is that the agreement in the classification leaves something to be desired. No doubt the difference would be even larger for ones using different classification schemes. It is worth pointing out, that the signal-to-noise in a one arc-second pixel, 0.5 mag above the detection threshold is a bit less than 5.0. Therefore, for a galaxy occupying a few square arc-seconds of area, the S/N will be in the range of 10 to 20, which puts a severe limit on the reliability of any separation scheme. A great deal of progress has been made in this field during the past few years, but it is apparent that the fundamental limits to the classifiers in the presence of substantial amounts of noise, and outside the 'training set' needs to be defined more carefully.

2. The Future Role of CCDs in Wide-field Astrometry

The title of this section might be appropriately sub-titled 'Photographic' Astrometry after there are no Photographic Plates, What Now? For with the recent announcement by Eastman Kodak Co. that they will no longer produce the emulsions that are used in photographic astrometry and the probability that the IIIa- and IV plates will soon follow, it is clear that we either have to go to other sources for the plates, such as ORWO (Ohnesorge 1993) in Germany or P. Sheglov (Birulya et al. 1993; Sheglov 1993) and associates in Russia. Alternatively, we need to look at different types of detectors such as CCDs, which given their very high quantum efficiency, albeit small dimensions, might prove to be a satisfactory substitute. It is therefore the purpose of the following sections to explore two modes of operation which might be usable for wide-field astrometry.

2.1 STARE MODE CCDs

The first and most obvious mode of operation is to use the CCD as if it were a photographic plate and simply guide for an extended period of time. Given the high quantum efficiency of the CCD it is possible to reach very faint limiting magnitudes in a short time, but the limitation on the size of the chips means that many exposures must be linked together before a reasonable number of reference stars are available to transform the derived positions into a standard system. For example, a 1024 x 1024 chip covers about 15 x 15 arcmin of the sky; and in order to achieve uniform system capable of being transformed into a standard astrometric system such as the ACRS (Urban 1993) or PPM (Roeser 1990), it would probably be necessary to have a corner to center overlap in the exposures. With that amount of overlap it should be possible to mathematically combine the CCD exposures without any loss of positional accuracy using the 'Plate Overlap' method of Eichhorn (1960, 1974). Assuming 60-second exposures, a similar amount of time to read the chip and move to the next region, and a 40% efficiency to account for the weather and the moon yields about 16 years to cover one hemisphere. Obviously it would be possible to decrease the time drastically by placing more CCDs in the focal plane, or by using larger CCDs. For example, a 2 x 2 array of the above chips would reduce the time by a factor of four, or a similar array of 2048 x 2048 chips would reduce the time by a factor of sixteen. All that would be required would be the money to build the system!

Lindegren (1980) and Han (1989) have modelled the turbulence in the atmosphere and predict that the limiting unit weight precision for *differential* astrometry is about ±0.020", in contrast to direct positional measurements which is appropriate for the drift scan mode. With a pixel size of about 0.8", 1/40th of a pixel centroiding precision would be required, which is much too optimistic for such a large pixel size. However, 1/15th should be possible, which yields ±0.05" for the unit weight precision; in other words the precision should not be limited by the atmosphere.

Benedict et al. (1991) have conducted an experiment that is a hybrid between the Stare and Drift Scan modes using the Steward Observatory CCD/Transit Instrument, which is a zenith-pointing 1.8-meter reflector that operates in the Drift Scan mode. They have analyzed the precision of the relative astrometry within a 8.25 x 12.5 arc minute section of the sky based on repeated scans of the same area. Using only a moment analysis of the 1.55" pixels, the astrometric precision that they derive is ±0.050" for stars brighter than 16 visual (scaled to a one-meter aperture), which is in excellent agreement with the above estimates.

2.2 DRIFT SCANNING CCDs

The second mode of operation is known as Drift Scanning, because the telescope drive is turned off and the field of stars is allowed to drift across the CCD. If the CCD is aligned so that the rows are parallel to the diurnal path of the stars, then the stars will move slowly along a row without vertical motion. Each star would then expose a full row of pixels to a level dependent on its brightness. If, on the other hand, the charge in the CCD were moved across the CCD in synchronism with the diurnal motion of the sky, then all of the light from the star would be captured in 'one' effective pixel; and no smearing would result. Such a procedure is in use for a number of projects ranging from astrometry (Monet 1991; Stone 1993) to the search for near earth asteroids (Gehrels et al. 1990) to the determination of positions of stars and galaxies for cosmological studies (Shectman et al. 1992).

The main requirements for drift scanning are that the telescope be rigid or its metrology precisely monitored, the CCD clock be very stable and a large fast memory be available for the computer so that the data can be captured as it is read off the chip. For an example of this method, we take the system at Las Campanas which uses a 2048 x 2048 CCD read as a 1024 x 1024 chip with an effective pixel size of 15 µm, or 0.8"/pixel. The clock rate is adjusted to the diurnal rate so that no smearing occurs after the star has traversed 1024 pixels. Since the diurnal rate in the focal plane is a function of the declination, the 'height' of the CCD must be limited as a properly adjusted clock at the bottom of the chip will produce smearing at the top. This effect is large enough so that even at a declination of 12 degrees, a clock rate set for the bottom of the chip will smear the image by one pixel at the top. In addition, the diurnal path is really an arc so the width of the chip is also limited by the declination. There are solutions to these problems such as taking multiple exposures on a chip instead of integrating during the complete transit, and using several small chips displaced in declination, each with its own clock rate. Alternately as with the Sloan Digital Sky Survey (Lupton 1993) the telescope can be driven along a great circle to avoid the smearing limitation, but then severe constraints are put on the stability of the drive mechanism for the telescope.

If, on successive nights, the telescope is offset in declination such that the scans overlap by say 10%, then the long strips can be tied together by requiring that the positions of the many stars in the overlap be coincident. The relationship between the strips may be more complicated than just a constant since if the clock rate has changed then the scale factor in the time coordinate will differ. The main requirements are then that the clock be stable throughout one night and that the telescope either not move during the night or that precision metrology be available to monitor its position. Once a sufficient number of scans have been tied together, the composite scan can be put on the system of an external catalogue, such as the ACRS, PPM, or HST Guide Star Catalogue (Lasker et al. 1990). Due to the dynamic range limitations of CCD detectors, it would probably be necessary to use a wire objective grating with a magnitude difference of approximately 3 - 4 mag between the first and zero-order images so that the brighter calibration stars can be reached simultaneously with the faint stars and galaxies. The HST GSC might also be used here in spite of the modelling problems with the large Schmidts, since the transformation of the composite strip is only setting a zero-point, scale and orientation, and would be averaging over many plates and boundaries between plates, however that approach would have to be looked at carefully. Transformations into the HST GSC of a composite strip consisting of seven 15 arcminute wide declination strips covering a total area of 1.5 x 6 degrees with the Las Campanas system clearly show the systematic errors in the HST GSC positions across one of the Schmidt plates. Transformations that globally include many plates should average those errors.

A comparison between the x and y coordinates in the overlap portions in two adjacent strips shows accidental unit weight errors of approximately ±0.12" and ±0.11" in right ascension and declination respectively for the Las Campanas one-meter reflector, while Stone (1993) shows that the right ascension error for the U.S. Naval Observatory's 20 cm CCD Transit Telescope at Flagstaff is ±0.10". In the former case, the positions were derived from the data using a simple first moments analysis, while in the latter case considerable care was taken in the derivation of the positions; more about that later.

The accuracy of the photometry depends not only on the transformation to the standard system but also on the dynamic range of the CCD, which varies according to the full well of the specific chip. Based on a comparison of the magnitudes in the overlap region of the Las Campanas data, we estimate that its dynamic range is about 3.5 mag, limited on the bright end by saturation and bleeding and on the faint end by photon noise. The faint limit could be pushed a magnitude fainter by accepting larger photon noise, but no brighter since at saturation both positional and brightness information are destroyed. The USNO chip appears to have a larger dynamic range, extending some 6.5 mag. In both cases the range could be extended by another 4 mag by using a wire objective grating. Scaling the USNO data to the Las Campanas aperture shows that a one-meter telescope should have a limiting magnitude for a 60 second drift scan across the chip of about 18 to 19.

The fundamental limit on the unit weight precision of drift scan astrometry appears to be set by the atmosphere. Høg (1968) and Lindegren (1980) have developed models for turbulence in the atmosphere and derive different formulae for the long term refraction variations, however both predict the limit for 60 seconds of integration to be ±0.12", in remarkable agreement with the above results from two very different telescopes. Perhaps that indicates that telescope instability is not a major problem under good conditions and that image centroiding is not too important; if the latter is true, then it may be possible to centroid the images as the data are being taken and avoid collecting gigabytes of data each night. The limit to the precision could of course be improved by scanning the region more than once.

The length of time required to scan one hemisphere may be estimated by assuming that we observe one eight hour strip every night; therefore three nights would be required to scan 24 hours of right ascension. If we use a 15′ x 15′ CCD, and overlap the adjacent strips by 10%, then there are 400 strips from the equator to a pole, for a total of 1200 nights. Allowing 40% efficiency for clouds and the moon yields 8 years for a single coverage of a hemisphere. The use of two or four chips, spaced in declination, each with its own clock rate, would cut the time by a factor of two or four, respectively. In this case, the estimates are rather more difficult to make, since it is necessary to modify the observing procedures as the telescope moves close to the pole.

2.4 SUMMARY

Both the Stare mode and Drift Scan modes of creating astrometric catalogues appear to be feasible at the present time. It is likely that in order to operate a telescope in the Stare mode it would have to be automated at some level, otherwise the efficiency of the system would drop drastically. On the other hand, a telescope used in the Drift Scan mode might require some extra metrology to monitor its position. The precision of the resulting catalogues would appear to be about a factor of two better for the Stare mode (±0.050") than for the Drift Scan mode (±0.10"), although those figures are very rough estimates. I am sure that many individuals will be exploring the above possibilities and probably other potential replacements for photographic astrometry in the near future.

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