Photogrammetric Record, 10(58): 427–433 (October 1981)

AUTOMATED MEASUREMENT OF ASTRONOMICAL PHOTOGRAPHS

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(Paper read at the Technical Meeting of the Society on 17th February, 1981)

Abstract

The development of an automated photographic measuring system (APM) is described. A very accurate laser beam scanning microdensitometer is used to digitise the photographic plate and a series of on line computers analyses the data during scanning. The system is available as a national facility for United Kingdom astronomers and guest investigators.

INTRODUCTION

ASTRONOMERS have always been able to record information on photographic plates much faster than it could be analysed. A modern Schmidt telescope can record 10^6 astronomical images in an hour's exposure. About half of the images are those of stars which are always point-like objects and the rest are distant galaxies and other extragalactic objects (Fig. 1). Each 14 inch square (356 × 356 mm) photograph contains 4 billion bytes of information so that, in a single night, with one telescope, we may record 40 billion bytes of data. These panoramic detectors are used either to search for specific types of objects for later study or for collecting statistical data on the universe. At present, all plates are analysed visually by trained astronomers. Not only is this slow, but serious bias can be introduced into the selection of objects since only objects strikingly different from their neighbours are usually detected by eye. Our perception of distant parts of the universe can depend critically on what objects we choose to study and observational selection effects have plagued many areas of astronomy.

At the Institute of Astronomy in Cambridge, we have been developing an automated photographic measuring system (APM) for the UK Science and Engineering Research Council. This system is run as a national facility for UK astronomers and guest investigators. It consists of a very accurate laser beam scanning microdensitometer to digitise the plate and a series of on line computers to analyse the data as it is being scanned. Although the system is designed for general purpose photographic analysis, it is uniquely suited to searching for specific types of objects whose properties change from plate to plate.

A successful automated photographic measuring system must consist of two integrated parts, the microdensitometer which digitises the photograph and the computer analysing system. Possible approaches to implement these components are now discussed.

MICRODENSITOMETER DESIGN

In the past, the main limitation in machine measurement of photographs has been our ability to digitise accurately the fluctuations in plate transmission. This is no longer a problem using laser beam or charge coupled device (CCD) detector technologies. The conventional microdensitometer focuses an image of an aperture onto the photograph which is then refocused onto a secondary aperture before going into a photodetector. The second slit controls the scattered light in the optics. The plate is moved under the slit.

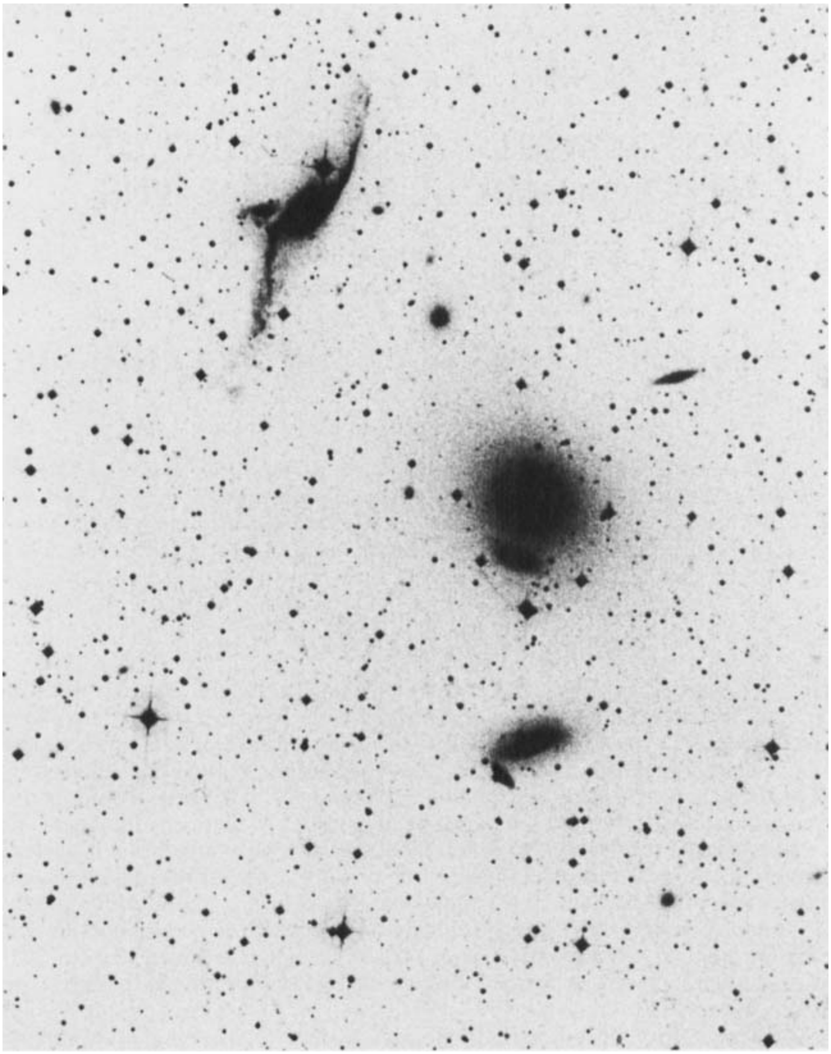

FIG. 1. A typical astronomical photographic record taken with a Schmidt telescope.

Three factors limit performance:

- (i) the inertia of the plate carriage;
- (ii) the brightness of the light source (photon noise); and
- (iii) for small spot sizes, the light incident on the plate becomes partially coherent and the measured transmission depends on the phase variations of the emulsion and not simply on the mass of silver per unit volume.

Nevertheless, microdensitometers such as the PDS are available which can sample up to 10 000 samples per second over large areas.

For higher speeds, flying spot microdensitometers must be used. Cathode ray tube (CRT) scanners have been used for many years but they have low photometric accuracy and, in particular, a bright halo which limits the measurement of small objects with high contrast. They also suffer from low light output. The APM system uses a laser beam flying spot scanner. The beam is deflected electronically using an acousto-optic deflector. This uses a sound wave to diffract part of the incident beam. By changing the frequency of the sound wave, we can alter the angle of diffraction and hence deflect the beam. The response time of these deflectors is a few microseconds and scanning speeds of 10^7 samples per second are possible. The halo of the spot is small and the limiting factors in speed are caused either by saturation of the photomultiplier or, if photodiodes are used, heat damage to the emulsion. (A 10 μm spot heats the emulsion by about 30 °C mW^{-1} of incident power.) Another technology which achieves comparable speeds is the CCD array. The photometric accuracy is lower due to scattering within the emulsion and cross talk between diodes but their performance is improving all the time. The development of these types of scanner means that we can digitise a 35 mm frame to 10 μm resolution in a few seconds. The problem now is to build computers that can analyse the data at the same speed and this is the same problem whether the input data comes from a photograph or a television picture from a satellite.

AUTOMATED PICTURE ANALYSIS

At the moment, computer programs are not good at recognising complex patterns. Because of this, effective picture analysis seems to be subdivided into two distinct areas:

(ii) *parameterisation* in which images of objects are described by a small set of numbers. These numbers are then used to classify the types of objects. This is the only way at present of doing automatic computer analysis; and

(ii) *interactive computing* in which the properties of the whole digitised picture are manipulated by the computer (for example, filtering, background removal and pseudo-colour display) and presented to the operator.

Effective parameterisation depends on the type of object we are looking for: St. Paul's Cathedral is difficult to parameterise in a few numbers. In astronomy, most of the images have a simple structure and special purpose very fast computers can be built to derive parameters for such images.

DESCRIPTION OF THE APM MACHINE

The APM system consists of a microdensitometer for digitising the plate and a series of on line computers for analysing the data.

Microdensitometer

The microdensitometer can handle plates up to 14 inch square (356 × 356 mm) and it uses a massive X/Y table to position the plate under a laser beam scanner with great accuracy.

Normally, one of two modes is used:

(i) an *area scan* in which the 16 000 mm^2 areas are completely scanned in 8 μm intervals at a rate of up to 240 000 samples per second. The transmission is digitised to 12 bits. The data are processed to derive a number of parameters for each image with an accuracy determined by photographic grain noise; or

(ii) an *image scan* in which individual images of known position (obtained either by visual inspection using the TV camera or from the initial area scan) are microphotometered. These data are used either to produce contour maps or to allow further computer processing such as the calculation of radial Fourier harmonics of galactic images.

The microdensitometer is basically a flying spot scanner and as such has somewhat lower photometric accuracy than the best two slit microdensitometers. The scanner can work in two other modes for higher accuracy but at slower speeds.

The layout of the microdensitometer is shown in Fig. 2 and consists of the following components.

(a) An *X/Y table* that holds the plate platen. Plates of up to 14 inch square (356 × 356 mm) are clamped against the platen. The platen can be rotated through an angle of ±4° and also holds a calibration graticule used to check for systematic drifts in position (caused by changes of temperature). The co-ordinate table weighs 5·5 t and is designed to have a maximum positioning error of ±0·3 μm.

(b) An *upper optical unit* that scans the plate. This is retracted for plate insertion but normally sits over the plate. The plate is scanned by a laser beam generated from a 5 mW He–Ne (helium neon) laser. The beam is deflected into a line raster scan about 2·0 mm long by an acousto-optic deflector. The beam is then split, half going to a photomultiplier and the rest towards the plate. The photomultiplier provides feedback signals to an electrooptic cell to stabilise the laser beam intensity. Control to 0·2 per cent is achieved by this servo loop.

The other half of the beam is refocused onto the plate and moved over a square centimetre by angular rotation of two mirrors (the X and Y *area scan deflectors*). By using air bearings to define the rotation axes and interferometers to measure angular displacements, we can position the mirrors to ±0″·2 (corresponding to ±0·3 μm on the plate) with settling times of less than 20 ms. This deflection system was developed for the prototype but is not used since it is more efficient to scan the plate in large areas of 16 000 mm^2 (the area scan deflector only covers 100 mm^2) by slewing the X/Y table.

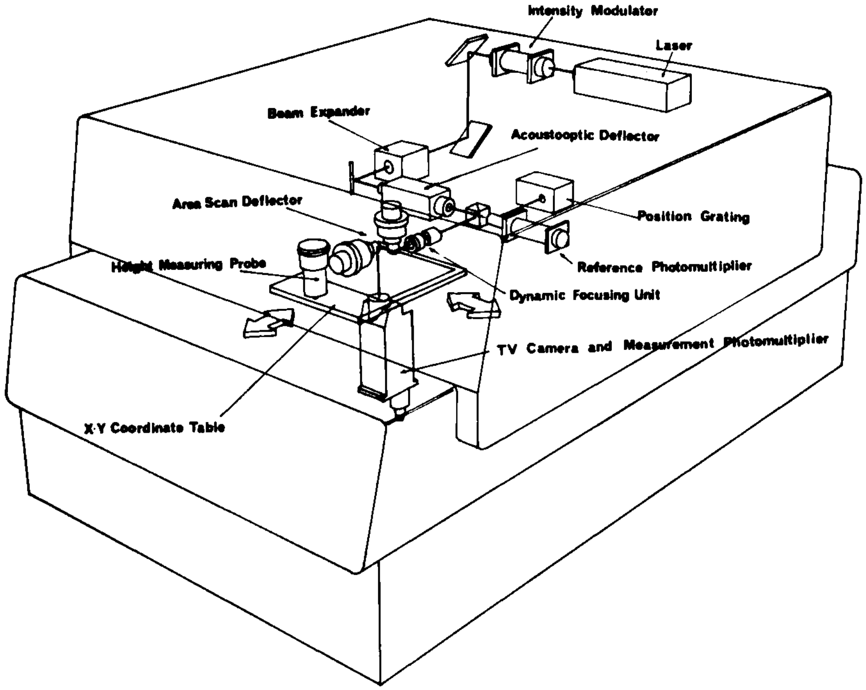

FIG. 2. The automated photographic measuring system microdensitometer.

Focus is maintained by dithering the lens over a distance of a few micrometres and locking onto the grain noise of the emulsion. The lens position is servo-controlled to maximise the grain noise. The change in spot size introduced is less than 0·5 μm in a 8 μm spot. A focusing accuracy of ±5 μm is achieved.

(c) When the light has passed through the plate it is collected by the *lower optical unit*. A television camera is provided for visual inspection and initial alignment of the plate. A photomultiplier is used to measure the diffuse plate transmission.

IMAGE ANALYSIS HARDWARE

Special computer hardware is available in the APM system for the determination of parameters of individual images from a raster scan of the plate. To be useful astronomically, these parameters should (i) give essentially complete information of the shape and position of the images, at least for the numerous faint images; (ii) work to as low a limiting isophote as possible (our ability to distinguish between faint stars and galaxies depends largely on the faintness of the lowest isophote which we can reach); and (iii) detect the presence of overlapping images. Ideally the system should be able to separate such images. Conditions (ii) and (iii) are linked, since more and more images overlap as the limiting isophote is reduced.

Low isophotes also pose a computational problem. The simplest method of separating images is to set a threshold a fixed magnitude above the background and only accept points above this threshold as belonging to images. A low threshold means:

(i) the local background must be known extremely accurately. For faint or diffuse images a 1 per cent error in background can cause more than a 10 per cent error in integrated brightness, which is an unacceptable error for most astronomical programs; and

(ii) the hardware must be able to deal with the enormous number of spurious "images" which appear above threshold and which are caused by random fluctuations in grain density. At a threshold equivalent to 1 r.m.s. deviation of the noise, this number exceeds $500\,\mathrm{mm}^{-2}$.

From considerations of the information content of images of faint galaxies, we can show that the low order moments and areal profile of the image down to a low isophote give almost complete information about the image (at least for images of $m > 16$). Since these parameters can be readily computed they are used to define the images in the image analysis computer.

A block diagram of the computer system is shown in Fig. 3. The plate is usually scanned in a series of $16\,000\,\mathrm{mm}^2$ areas and each area is scanned in 64 columns, 256 samples across and 16 384 samples downwards. The 12 bit transmission level is converted to a 10 bit intensity estimate *via* a small random access memory used as a look up table. The table is programmed from data derived from the plate calibration curve which must be obtained by the investigator. As a default condition (when no such data are available), conversion to density (logarithm of transmission) will be used. Over most of the dynamic range of well exposed plates, the density is approximately proportional to the original intensity of light on the plate. These data are then processed by the image analysis hardware.

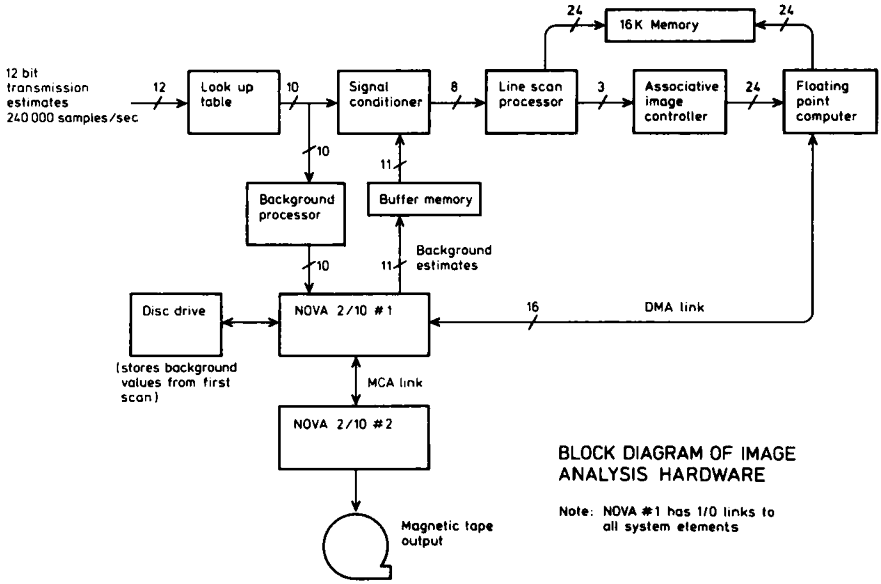

FIG. 3.

The image analysis hardware consists of a pipeline processor and a programmable very fast floating point computer. The operation of the units is controlled by a Nova 2/10 computer that can be programmed in a high level language. As the name suggests, the pipeline processor consists of a series of hardware devices that operate on the data in sequence. The processor consists of four units:

(i) *a signal conditioner* which can be programmed to

(a) smooth data over a 1 × 1, 2 × 2 or 4 × 4 area of sample points and

(b) remove small images between 5 μm to 30 μm (programmable in steps of 5 μm) in maximum extent. This cuts down the number of noise images by a substantial factor while leaving bigger images completely unchanged. This feature speeds up the hardware but does not affect the basic operation of the system;

(ii) a *background processor* that derives maximum likelihood estimations of the background all over the plate. A fixed threshold level is added to the local background estimate and every data point compared to this level. Only points above the threshold are processed;

(iii) a *line scan processor* which derives parameters for each set of contiguous samples above the machine threshold; and

(iv) an *associative image controller* which determines which slice belongs to which image.

Since the smallest real image is some 20 μm or more in diameter and since the plate is sampled every 8 μm, all images are scanned a number of times. Parameters for individual slices obtained by the line scan processor must be combined for the whole image. The associative controller carries out this task, assigning areas of core memory to connected slices in a 16K × 24 bit word buffer memory. This memory enables the floating point computer, which carries out the combination of all the slices of individual images, to work asynchronously with the microdensitometer scanning. The associative controller tells this computer where the relevant data are stored. All these data are fed into a programmable computer which determines the parameters for individual images and sets this information on magnetic tape *via* a Nova computer. Key features of the system are its speed, flexibility and ability to determine the most significant parameters for most of the images on the plate. As an example of its use, the automatic detection of QSOs will be briefly discussed.

Quasi-stellar objects (QSOs) are very active massive objects, possibly powered by a central black hole. They are as massive as entire galaxies and are so bright they can be seen at distances such that their light takes billions of years to reach us. They are intrinsically interesting and statistical studies of their properties may enable us to unravel the early history of the universe. There are perhaps a hundred QSOs on an average Schmidt plate (35 square degrees of sky) and as photographic images they are virtually indistinguishable from stars in our own galaxy. They can only be identified by comparison of a number of plates, each taken under different conditions, involving different wavelength bands, polarisation filters or different times. Fig. 4 shows the steps in the process of finding QSOs

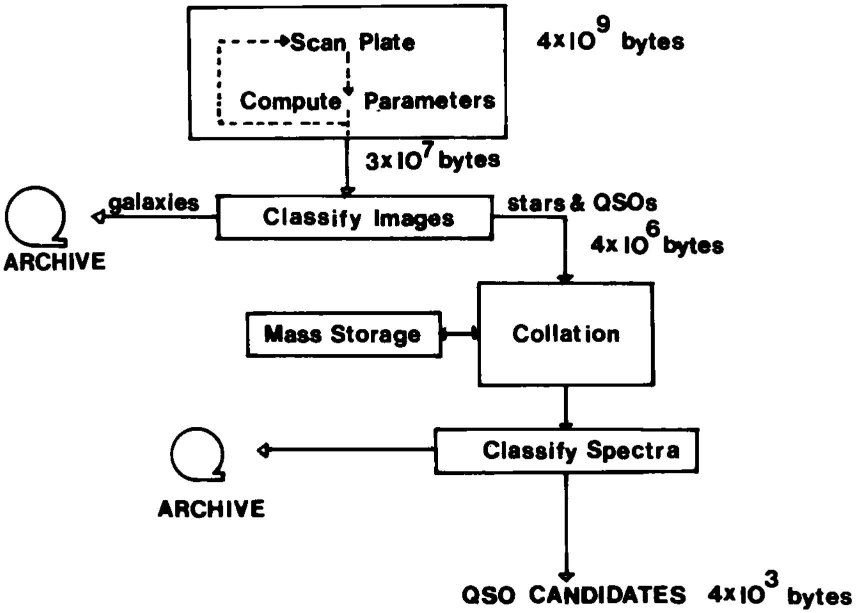

FIG. 4. Steps in the process of finding quasi-stellar objects (QSOs).

and the amount of data generated at each stage. The plate is scanned point by point in a raster and the samples are fed into the processor that detects all the images above the sky background and determines their parameters. The parameters are then classified according to their shape using special learning algorithms. We know QSOs are stellar in shape, so only point-like images are further processed. Thus all shape information may now be rejected and we are left with an 8 byte vector of position and intensity (2 × 24 bit words, 1 × 16 bit word) for each object. These data are stored on disc. We scan a number of plates of the same area of sky, taken in different colours, and the data for the same objects are collated. The broad band spectra of the objects are then classified. Because we do not wish to throw away any candidate QSOs, we use similar algorithms to those used for shape classification. These recognise "common" types of spectra (due to stars) and once these are eliminated from the data base, we are left with a small sample of candidate objects all of which differ significantly from field objects. Nearly all of these objects are interesting, even though a substantial fraction may be rare types of star, but we can only perform the final separation into stars and QSOs by further observation using big telescopes.

Thus the APM system has filtered out only a very small number of objects of specific type from the enormous amount of data available on the plate. Such on line filtering allows us to optimise our search procedures for certain types of object in an essentially unbiased manner and at economic cost.

NOTE AND ACKNOWLEDGEMENT

At present the system has mainly analysed astronomical photographs. The microdensitometer and much of the computing hardware are directly applicable to a wide range of other photogrammetric problems.

The support throughout this work of the Science and Engineering Research Council is gratefully acknowledged. The system is run as a national facility for UK astronomers. Parties interested in using the facility for other uses should write to Dr. E. J. Kibblewhite, Institute of Astronomy, Madingley Road, Cambridge CB3 0HA.

Résumé

On décrit un systéme automatisé de saisie de données sur cliché. Un microdensitométre à laser numérise la plaque photographique et les données sont analysées en temps réel par ordinateur. Le systéme est destiné aux astronomes du Royaume Uni et aux chercheurs y séjournant.

Zusammenfassung

Beschreibung eines automatisierten photographischen Messsystems (APM). Ein hochgenaues Laser-Mikrodensitometer wird dabei zur Digitalisierung der Bilder benutzt, und eine Serie von On-line-Rechnern analysiert die Daten während der Abtastung. Das System steht für Astronomen im Vereinigten Königreich und anderen Forschern zur Verfügung.