The Design and Development of the GALAXY Machine

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HISTORY OF THE GALAXY PROJECT

The requirement for a machine of the GALAXY type arose from the large amount of information made available by the photographic plates from Schmidt telescopes. Even a small telescope of this type will produce many thousands of well-defined images per square degree on a single plate. Previously only a few selected images could be measured for position or magnitude in order to keep pace with the production of plates.

It occurred to Dr P. B. Fellgett (now Professor of Cybernetics and Instrument Physics at Reading University) that if a general purpose computer could be applied to the problem, full use could be made of the vast amount of information stored on the plates. There was however one link missing in the chain, a means of converting the photographic data into a computer-compatible form. Thus were formulated the requirements for a machine to perform this latter operation—that it should be a general purpose equipment, *i.e.* measure both position and brightness of images simultaneously, that it should automatically find and measure all images on the plate, and that measurements should be improved by optimization of the statistical probability of the grain distribution in the image for position and brightness simultaneously. The proposed machine was therefore given the name GALAXY, an acronym for General Automatic Luminosity and X-Y measuring engine.

Dr Fellgett then outlined the salient features of a proposed design—a precise mechanical carriage based on kinematic principles to support the plate below cathode ray tube scanning systems, accurate measuring systems to give at all times the exact location of the carriage, servo systems to control the latter, and an electronic unit for supervisory control and data handling. Two scanning systems were decided upon to allow the operation to be broken down into two parts, the searching of the plate for the approximate location of images and the measuring of these images. The reasons for this are firstly that the area occupied by images is only of the order of one hundredth of the total area of the plate, leading to an enormous time saving by carrying out a preliminary search operation, and secondly that editing is made possible at the paper tape link between the two processes.

After a design study carried out by the Instrument Control Department of Ferranti Limited Dalkeith, Midlothian, now Faul-Coradi Scotland Limited, Haddington, East Lothian, and Dr V. C. Reddish of the Royal Observatory, Edinburgh, astronomical consultant for the entire project, a contract was placed for the detailed engineering design and construction in August 1966 by the Science Research Council. Mechanical design of the machine itself was carried out by Hudson Drawing Services, Luton, and the construction by Sogenique (Service) Ltd., Newport Pagnell. Ferranti Limited, Moston, Manchester, designed and supplied the scanning systems, and Faul-Coradi Scotland Limited were responsible for the design and production of the electronic control system and for the installation and commissioning of the complete equipment.

After installation at the Royal Observatory, Edinburgh, the testing of the complete system began in March 1969, and by June the performance was exceeding specification requirements, namely that the position of images should be determined to 1 micron accuracy and the size to 0.25 micron, and that images should be automatically found and measured at a rate of 1000 per hour. Exhaustive tests during the following months showed that performance was being maintained, and the Observatory officially accepted GALAXY in October 1969, when it began regular work on astronomical programmes.

THE GALAXY MACHINE

The machine consists of a hollow webbed base casting on which is mounted a carriage with compounded X and Y movements on Schneeberger linear ball bearings with a high degree of linearity and orthogonality. Three V-grooves are mounted on the carriage which locate three ball-ended screws on the plate carrier. Two cathode-ray tubes of the micro-spot type with their scanning assemblies and

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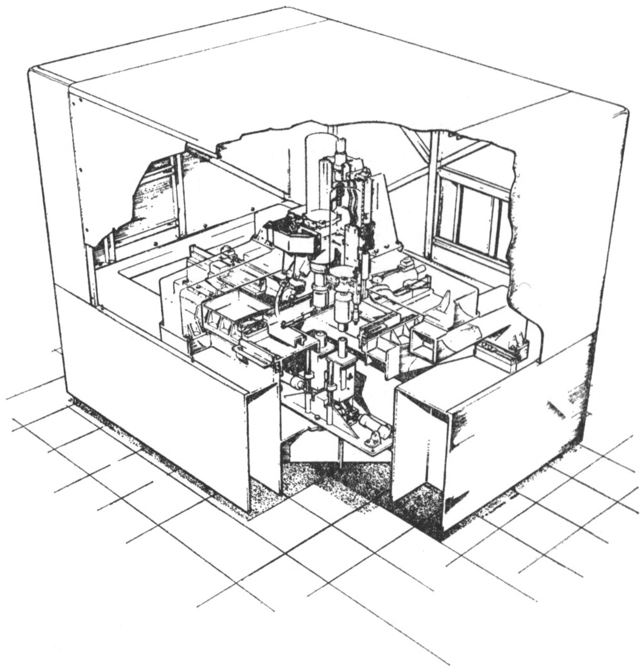
optical systems are rigidly mounted on a bridge casting over the carriage, so that the plate can be positioned relative to their optical axes, the resulting variations of light transmission being detected by two photomultipliers mounted below the carriage level. The maximum plate size accommodated is 254 mm square.

Carriage movements are actuated by two hydraulic rams controlled by electro-hydraulic valves, operated by servo amplifiers to which position and velocity feedback are applied. The traverse of the rams is 456 mm in X and 302 mm in Y, the extra movement in X being necessitated by the distance between centres of the two scanning systems. Oil at a pressure of 70 Kg per sq. cm is supplied to the hydraulic system by a remotely mounted swash-plate type power unit.



— CUTAWAY DRAWING OF GALAXY —

X and Y movements are measured by a refinement of the moiré grating system originally designed by Ferranti Limited, Edinburgh, for use on numerically controlled machine tools. Each axis is provided with a 100 lines per mm glass grating which is examined by a reading head containing an index grating of identical line structure, a source of parallel light and a group of four photo-detectors. The unit is adjusted to produce quadrature paraphase signals resulting from movement of moiré bands when relative movement occurs between the two gratings. Since the main grating is rigidly fixed to the machine base and the reading head to the carriage, this gives a measure of the movement of the latter. Circuitry is provided in the control unit to accurately digitize the output signal in tenths of a grating cycle, giving a unit of measurement of 1 micron.

Sheet steel cladding is provided to exclude stray light, giving overall dimensions for the machine of 2.5 m × 1.9 m × 2.2 m high. The overall weight is 3.6 tons, supported on three adjustable jacking screws which rest on a concrete foundation. An air conditioning plant maintains the environment at 20° ± 0.5°C with not more than 50 per cent relative humidity, and micronic dust filtration is provided.

THE ELECTRONIC CONTROL UNIT

The electronic control unit consists of two standard racks mounted side by side in a single unit 1340 mm × 660 mm × 1880 mm high. Sixteen sub-units accommodate a control panel, scanning electronics, a core store, a monitor oscilloscope, various power supplies, and a number of card boxes each holding a maximum of 28 circuit cards.

Circuits are assembled on plug-in 228 mm × 152 mm printed circuit or part printed part wired cards. Discrete component construction is used in some parts of the equipment, whereas RTL logic and linear microcircuits appear in other parts.

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Output-input facilities are provided by a high speed paper tape punch and a high speed photoelectric tape reader. These are housed in a separate room to avoid dust problems.

THE SEARCH OPERATION

Since the carriage position measuring system is of the differential or variable datum type, it is necessary to relate the datum to the search optic axis before starting to search the plate. This is carried out by an automatic datum routine.

The line scan on the C.R.T. is projected at a 4 : 1 reduction on to the emulsion plane by a process lens, giving a scanned length at the plate of 8.192 mm. Transmitted light is conducted to a photomultiplier by a perspex light pipe placed below the plate. An identical lens and mirrors cause a 64 micron pitch grating to be similarly scanned and examined by a second photomultiplier, whose output is synchronized to a clock waveform by a phase lock loop which controls the instantaneous scanning rate. This then allows distance along the scanned line to be accurately measured in terms of clock intervals. A third photomultiplier monitors the brightness of the C.R.T. spot and stabilizes it at a preset value by applying a feedback control to the cathode.

On starting the search operation the plate is automatically scanned in columns 8.192 mm wide between preset X and Y upper and lower limits by combining the C.R.T. line scan with a mechanical indexing of the carriage by the line thickness in the orthogonal direction and a column index in the direction parallel to the scan. The spot size, and hence line thickness, is selectable over the range 8, 16, 32, 64 microns and is chosen to conform to the size of the faintest image. Since the intensity distribution in the spot is gaussian it is a reasonable match to the transmission profile of this image, giving a high probability of detection. The speed at which the plate is scanned depends on the spot size setting, being 30 square mm per min for 16 microns, and other speeds proportionally.

The photomultiplier output is examined by a threshold detector whose level is preset to compromise between missed images and false detection due to grain clumps and photomultiplier shot noise. The resulting quantized signal is compared with the clock waveform representing increments equal to the spot size along the X scan, to give a pattern of black and white squares. 1024 addresses of the core store are used to accumulate the patterns from successive lines to build up a histogram of the images, *i.e.* at each address representing a distance along the X scan is stored the number of black squares for the particular image seen to date in the Y direction. Whenever an image is complete, the value of its Y diameter is transferred to the corresponding address in the other half of the store, which is scanned for punch-out data at the end of each line. The coordinates of images are found by adding the core store address to the value of the X present position counter and subtracting half the Y diameter from the Y present position. These are punched out on 8 channel paper tape to give a finding list for the measurement operation to an accuracy of between one and two spot diameters.

Also punched out periodically are the coordinates of a group of position and magnitude reference images which have been preselected and measured, and whose coordinates have been punched on a loop of tape which can be read and copied on to the output tape once every thousand stars found, along with reference identification markers. Repeated measurement of these references at hourly intervals in the measurement mode result, allowing long-term drift to be corrected during a computer reduction, and making the measurements independent of absolute calibration.

The rate of punch-out of image coordinates from a Schmidt photographic plate in the search mode is about 10 000 per hour, using a 16 micron spot size.

THE MEASUREMENT OPERATION

The measurement operation is preceded by a second automatic datum routine now to refer coordinates to the optical axis of the high magnification system. This system consists of a C.R.T. pseudo-spiral scan, *i.e.* 1024 concentric circles reduced optically 240 times to give an overall diameter of 256 microns at the emulsion plane. Since a short-focus objective is involved, the lenses are assembled in a stainless steel tube centred by an air bearing and weight-relieved pneumatically to give a downward thrust of the focussing nose-cone on the emulsion of about 3 g weight. This allows focus to be maintained in spite of variations in emulsion height. Transmitted light is conducted by a light pipe to a photomultiplier as in the search case. A second photomultiplier fed by a fibre optics ring viewing the spiral scan is used in a feedback loop to stabilize tube brightness. Lens systems using smaller reduction ratios may be used with plates having larger minimum sized images.

Each pair of coordinates is read in turn from the finding list by a photoelectric tape reader, to be

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followed by a digital positioning operation, using a proportional controlled approach, *i.e.* servo velocity proportional to distance to go within the last half mm, which brings the corresponding image into the field of view of the spiral scan. Control of the servos is now passed to signals derived from the

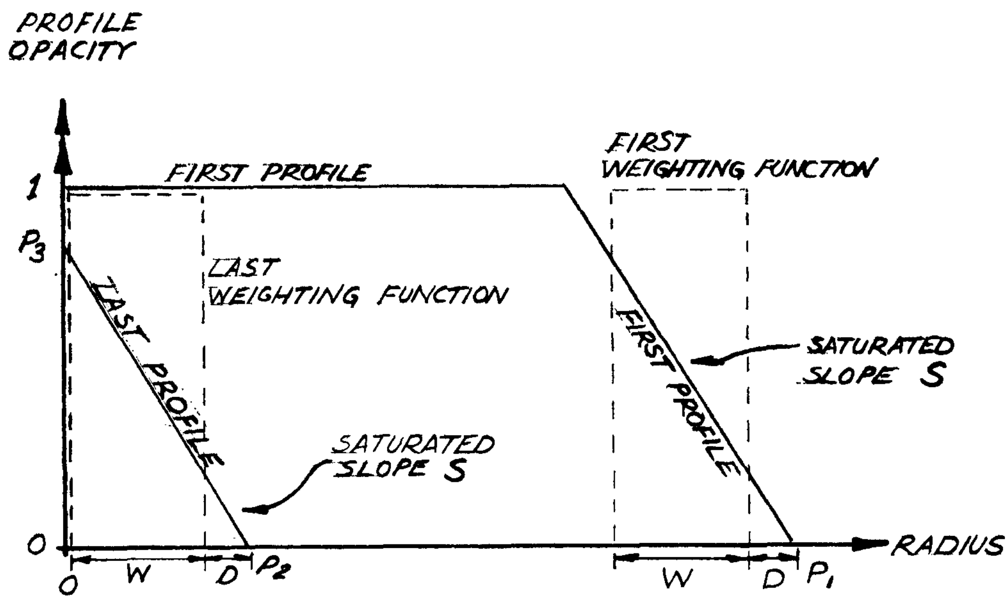

Fig. 1

output of the photomultiplier examining the light transmitted by the image, by applying this output to cosine- and sine-referenced synchronous detectors for X and Y respectively. Phasing is such as to cause the image to be centered in the spiral.

Comparison is now begun between the mean radial profile of transmission and one of a group of

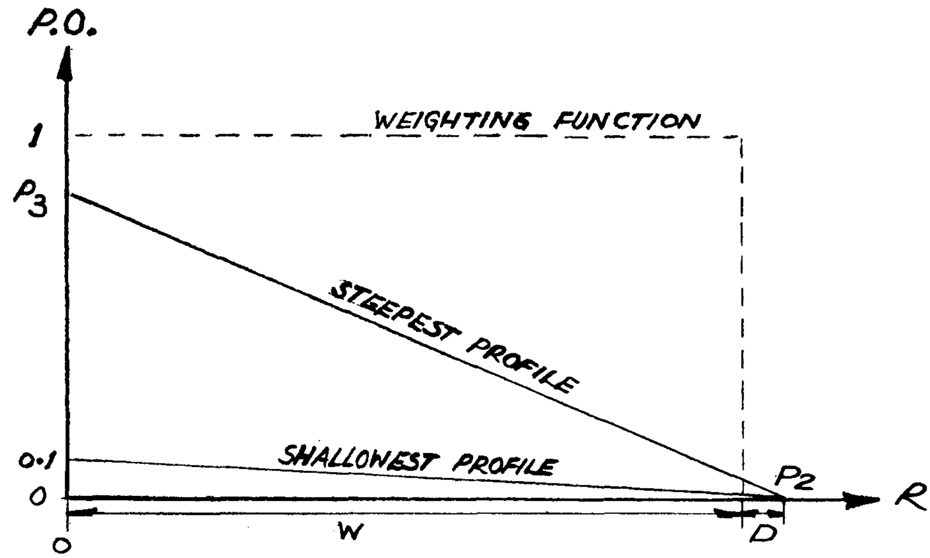

Fig. 2

1024 idealized profiles built up during the scan from data previously loaded into the core store from a profile program tape. These profiles are of two types, saturated and unsaturated, as shown in Figure 1 to Figure 3, the term referring to photographic saturation of the emulsion. The real profile, by comparison, has rounded corners and has noise superimposed. The horizontal parts, corresponding to

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the plate fog level at large radius and to saturation at small radius, contain no useful image information, the interesting part being the slope where transmission varies with radius. This is selected by a weighting function, which in this case is simply a gate function, starting a preset radial distance D from the lower corner and continuing for a preset radial width W. In the unsaturated profile case the function continues to zero radius.

Integration of the instantaneous profile difference is carried out over the weighting function width W, the integral being sampled by a comparator controlling the sense of idealized profile iteration towards a balance. Initially steps of 16 profiles are used until a reversal of comparator sign occurs, when reversion to unit steps takes place. On the second reversal of sign the balancing is assumed to be complete. Since the position of the weighting function is tied to the artificial profile rather than to the real one, and since it is also applied to the phase sensitive detectors in the servo channels, the image is viewed differently by the servos as iteration progresses. If due to asymmetry in the image this causes the servo error signals to exceed a threshold, iteration is interrupted until the servos have recentred the image. This demonstrates the interaction of positional and brightness measures as a result of the statistical nature of the grain distribution in the image. The method used optimizes the probability of these measures by making use of all the information available in the useful part of the image.

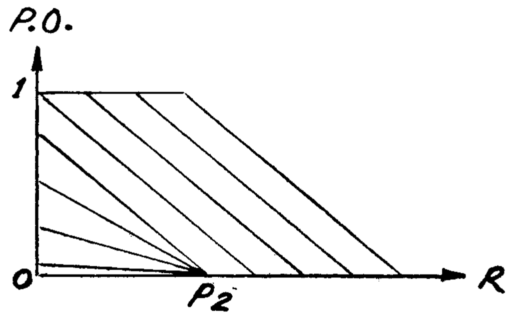

Fig. 3
Galaxy profiles and weighting functions

When both the centring and image balance conditions are satisfied, the image centre coordinates are punched out on 8 channel paper tape from the carriage present position counters, and the brightness information as the core store address of the matching profile. The latter is later reduced to a magnitude measure off-line by comparison with the brightness measures of the reference stars of known photoelectric magnitude. A stylized representation of the search and measurement phases is shown in Figure 4.

The time required for the above measure is on average 4 sec per star image, or 900 images per hour, amd so the reference stars are measured at about hourly intervals to give long term drift information. To cover the case of false image information from search, if no star is found a punch-out with a reject code occurs.

APPLICATIONS OF GALAXY

Although the GALAXY machine was designed to meet a specific requirement, namely to form a link in the chain of events from the Schmidt telescope to the computer, so that the vast amount of information available can be fully utilized in astronomical programs, it has however much wider possible applications, *e.g.* to other types of telescope plates, to satellite tracking photographs, to aerial survey photographs, or to microbiology. In fact GALAXY could be applied to most requirements for high speed precision measurement of micro-images on a photographic plate.

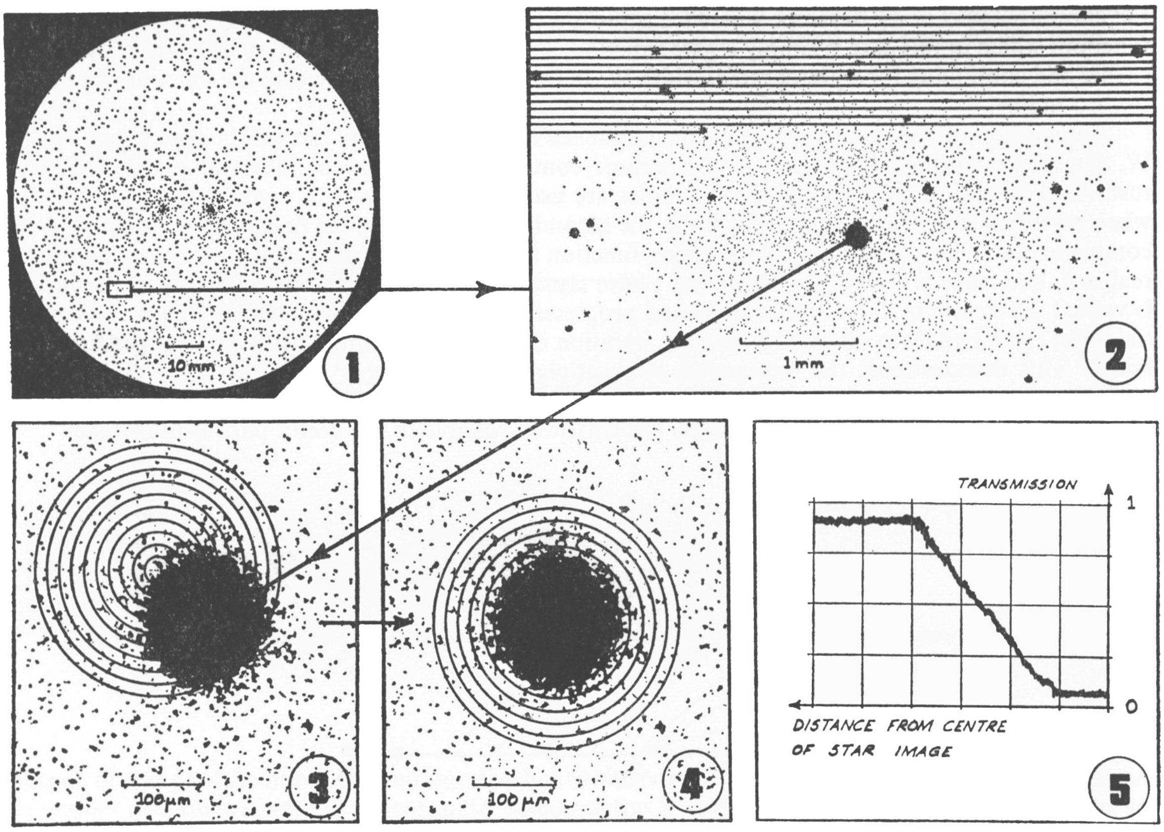

Fig. 4

Method of operation of the GALAXY measuring machine at the Royal Observatory, Edinburgh.
(1) A typical photograph taken with the Schmidt telescope. The stars have produced black images on the negative. A typical photograph contains 40 000 images. An area of the negative is selected for measurement.
(2) The selected area of the negative enlarged. GALAXY searches the selected area for star images, using linear scanning.
(3) A single star image greatly enlarged. GALAXY scans the star image, using concentric circle scanning.
(4) The same star image; GALAXY centres the star image and measures its position to 1 μm.
(5) Drawing of the oscilloscope display on GALAXY. The profile of the star image is measured with an uncertainty of 0.25 μm.

DISCUSSION

R. B. DUNN: If you started again, would you again use linear ball-bearings and hydraulic rams, or would you go to air-bearings, ball-bearing screws, and torque motors, as you did in the microphotometer described by Dr. Parks?

G. S. WALKER: Hydraulic rams and Schneeberger bearings were chosen because we had plenty of experience of them at the time when the design was frozen, namely seven to eight years ago. Our experience of air-bearings and torque motors has been gained over the last two to three years, and so if we were starting from scratch now we should probably use the latter design, although the design using hydraulic rams and Schneeberger bearings has proved itself to be better than specification, as borne out by the results to be described in Dr Pratt's paper.

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