An X-Y Programmed Microdensitometer for Star Spectra Analysis

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INTRODUCTION

The instrument described in this paper has been developed as the result of close collaboration over a number of years with the University of Utrecht.

It features a combination of advanced facilities which have not previously been available for such work.

The principal requirements from which the design evolved include:

1. High precision positioning of large spectrograms in two axes.
2. Scanning slits down to 5 microns width.
3. Adjustable orientation of scanning slits.
4. Density measurement range up to D = 4.
5. Visual monitoring during measurement.
6. Fully automatic measurement sequence under direct computer control.
7. Output on magnetic tape in I.B.M. compatible format.

OPTICAL SYSTEM

Densitometric System Design Considerations

The approach to the general problem of microdensitometry has been from the morphological viewpoint as expounded by Zwicky (1948). Briefly, the method may be summarized thus:

1. Formulation and generalization of the problem.
2. Enunciation of those parameters involved in its solution.
3. Deduction of the totality of solutions of the general problem.
4. Determination of the ideal performance of each of these solutions.

Now the object in microdensitometry is the determination of the optical transmittance of a selected small area of recorded image. This is achieved by comparing the intensities, in the presence and absence of the absorbing image, of a beam of light which has the desired cross section at the appropriate point in its path. Consequently the parameters of importance are the means of defining the operative cross section of the light beam and the procedure for comparing the measured intensity with some standard.

In the original study a third parameter, namely the means of measuring the light intensity, was also included. However for the purpose of this discussion the use of photomultipliers in a D.C. current measurement mode is assumed.

There are three ways in which the operative cross section of the light beam may be defined:

A. By juxtaposition of a physical aperture with the photographic image.
B. By superimposing on the photographic emulsion the projected image of an aperture.
C. By superimposing a mask on the projected image of the emulsion.

Three alternatives are offered by the second parameter also. The comparison of clear and attenuated beams may be made either:

D. Sequentially.
E. In rapid alternation.
F. Simultaneously.

These two sets of alternatives compound to give a gamut of nine basic microdensitometer configurations. While a quantitative evaluation of all these solutions has not been attempted, some

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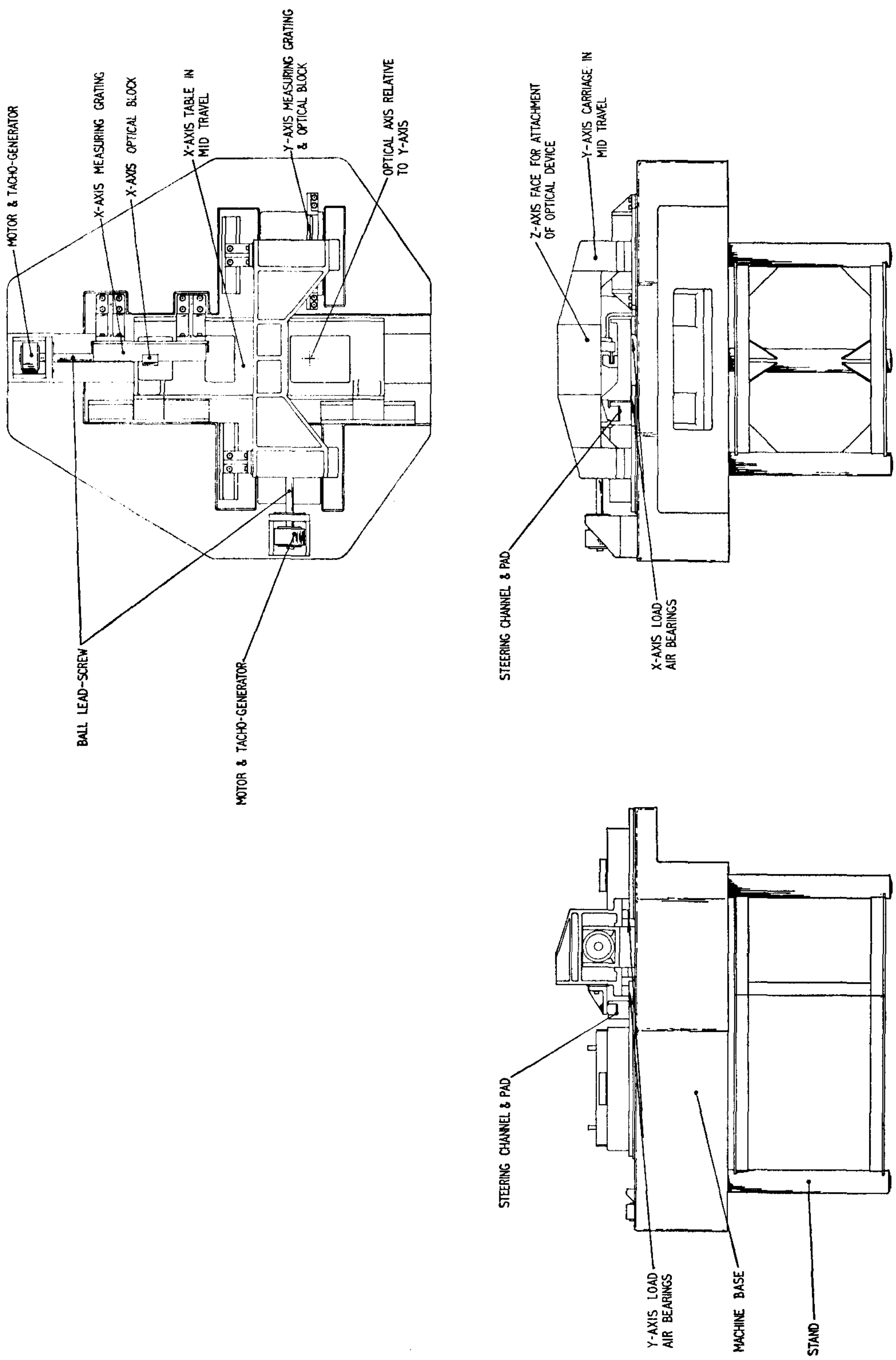

Fig. 1
General Arrangement of Mechanical Engine

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qualitative conclusions have been drawn; Table 1 indicates the most important characteristics of each alternative.

TABLE 1

THE MORPHOLOGY OF MICRODENSITOMETERS

Basic Design Factor	Alternative Methods A	B	C
	Juxtaposition of Slit and Emulsion	Slit Imaged on Emulsion	Emulsion Imaged on Slit
Method of defining scanning aperture	(+) Simplicity	(+) Low scatter (Illumination restricted to slit size)	(+) Convenient for image and slit monitoring
	(+) Can approach totally diffuse or totally specular measurement	(+) Constant geometry of postplate components irrespective of slit size	
	(−) Not feasible with very small apertures		(−) Illumination necessary over area longer than scanning slit
	(−) Possibility of emulsion damage		(−) Requires variable geometry on both sides of plate
	D	E	F
	Sequentially	Rapid Alternation	Simultaneously
Method of comparing transmitted beam with standard		(+) Lends itself to stable null balancing system	
		(+) Readily achieved logarithmic output	
	(−) Sensitive to variations in detector gain with time	(−) Mechanical chopper introduces vibration	(−) Sensitive to gain variations between two detectors
		(−) Null balancing system is slow in operation	

Some remarks on the resulting solutions should be noted. Firstly, alternative A is not applicable when, as in the present instrument, very narrow scanning apertures down to 5 microns width are required. This reduces the effective number of solutions to six. Of these, the two more commonly used involve alternatives C and D or E. A number of variants of these are already offered commercially and are further exemplified in work by Walker (1953), Altman and Stultz (1956), and Charman (1965) in particular.

The eventual choice of a single slit arrangement, variant B, has been influenced by three main factors:

1. The need to reduce scattered light to a minimum.
2. Accumulated experience with flying spot scanners, which are essentially single slit projectors.
3. The configuration of the mechanical engine, which does not readily allow the adjustment of slits on both sides of the spectrogram.

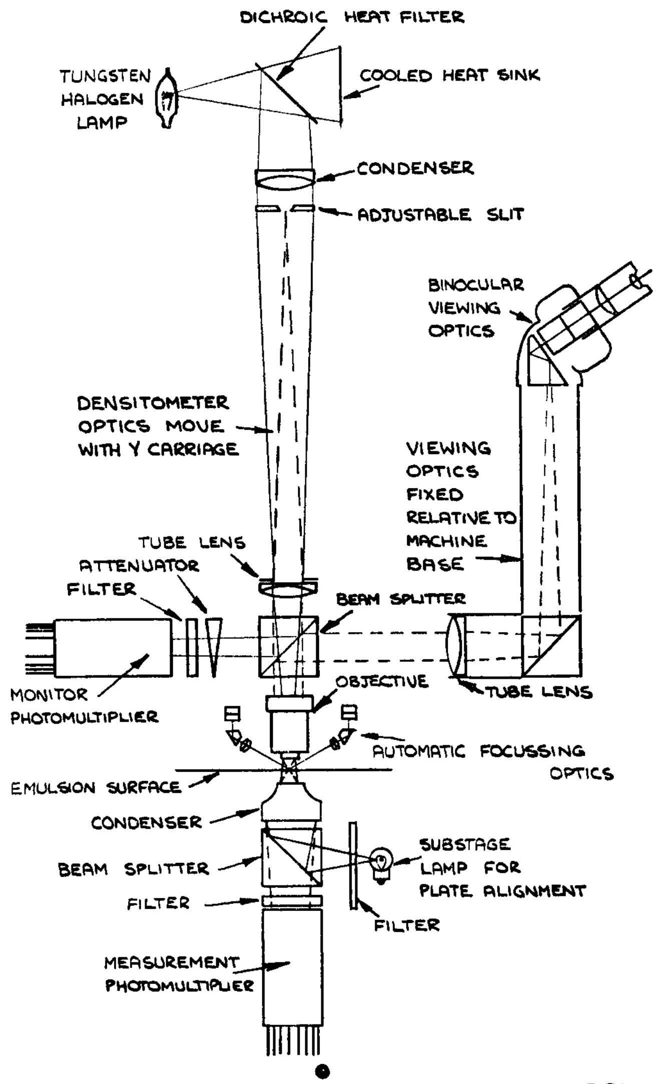
The selection of option F for the photometry was determined by the requirement for short measuring intervals and the availability of a particularly elegant and convenient measurement system which is described below.

Densitometer Optics

The optical system is illustrated in Figure 2. An adjustable slit is imaged on to the spectrogram by interchangeable microscope objectives using conventional Kohler illumination. A selectively reflecting mirror between slit and objective directs light to the monitoring photomultiplier. After passing through the spectrogram the measuring light is conveyed directly to the measuring photomultiplier.

Inspection of the spectrogram and slit image during setting-up and subsequent measurement is carried out by means of a binocular viewing system which projects through the fibreglass cover. This receives light from a variable intensity low-power source underneath the spectrogram via the monitor beam splitter, and from the slit image by back reflection. The spectrum of the background field illumination does not include the wavelength band employed for the measurement system.

The densitometer optics, mounted as they are on the upper and lower sections of the Y carriage, move with it through a stroke of 100 mm. As it is obviously undesirable for the viewing optics to do so also, the design makes use of microscope objectives corrected for use with an infinite tube length.



SCHEMATIC LAYOUT OF MICRODENSITOMETER OPTICS

Fig. 2

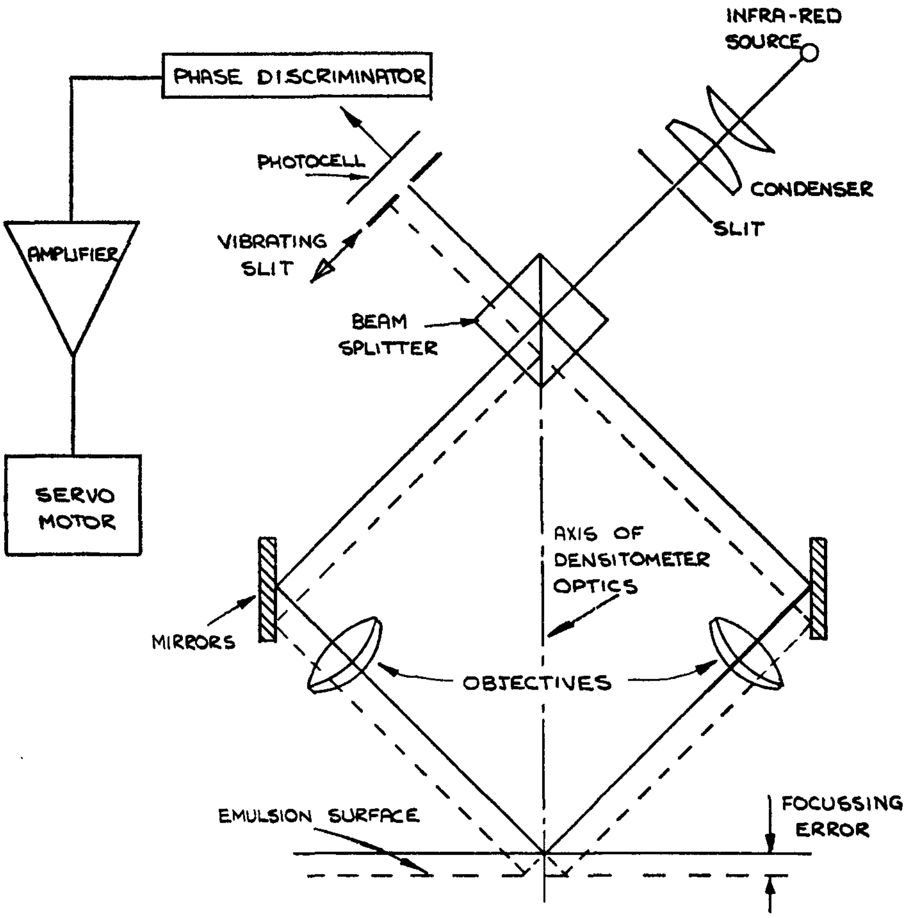
The parallel rays thus introduced between the objective and the tube length correcting lens of the viewing optics allow a variable path length without accompanying changes in magnification or focus.

Throughout the optical system great care is taken to reduce stray light to a minimum by carefully designed baffles and high-efficiency dead-black coatings. In accordance with the findings of Altman and Stultz this coating is applied also to the external parts of the optical system near the imaged slit. Altman (1966) has also investigated the question of background veiling in the images of fine slits.

In use, the optics are coarsely focussed so that the photograph surface is brought within range of an automatic focussing device, described below. The optics are then critically adjusted by inspecting the image quality at a fixed plane in the eyepiece. In this adjustment the objective is moved relative to the automatic system. The two systems are then locked together.

Automatic Focussing System

One recurring defect in microdensitometry is a failure to maintain sharp focus throughout long scans. Objectives capable of imaging very narrow slits are necessarily of wide aperture and consequently have only a small depth of focus. An objective of numerical aperture 0.25, for example, has a focussing tolerance of about ± 5 microns, a zone similar in thickness to the photographic silver image which is being scanned.



PRINCIPLE OF OPERATION OF AUTOMATIC FOCUSSING SYSTEM.

Fig. 3

While in the present instrument the plate carriage, throughout its travel, nowhere departs by as much as 2 microns from a fixed horizontal plane, the flatness tolerance of the plate itself is of course much less stringent. Plates coated on "selected flat glass" are flat only to within 25 microns in 25 mm. In consequence some automatic means of focus adjustment is necessary if the spatial frequency response of the scanning system is to remain acceptably constant throughout a measurement run.

The system described here and illustrated in Figure 3 has evolved from a patented optical probe developed by Bottomley (1967). A slit illuminated by an infra-red source is projected through a beam-splitter and imaged on to the emulsion surface by two separate objectives. The reflected beams are re-combined and the slit re-imaged on to a photocell. A vibrating slit aperture is interposed in front of the photocell to give an A.C. output for phase-sensitive detection.

Any departure of the emulsion surface from the ideal focus position causes a transverse deflection of the infra-red sensing beams, with a resulting shift in the position of the slit image on the vibrating aperture. Signals from the phase sensitive detector actuate a servo motor to re-position the complete optical unit, so that the scanning slit is brought again in focus in the plane of the spectrogram.

The symmetrical arrangement of the rays reflected from the emulsion renders the system insensitive to small changes in the angle of reflection from the surface. These merely broaden the final slit image without introducing any displacement errors.

Prototype instruments used as open loop position sensors have been tested on a variety of reflective surfaces. The results indicate that a focussing accuracy of ± 1.5 microns can be expected.

Density Measurement System

The photometric system employs two photomultipliers. The first of these monitors the source intensity while the second receives the light transmitted by the photograph. The outputs of the two detectors are compared in a patented logarithmic analogue-to-digital converter developed by Mallett and Arndt. The output thus appears as a density measurement in digital form.

In the A to D converter the voltages appearing across the anode loads of the two photomultipliers are each compared repeatedly with the decaying voltage across a capacitor with resistive load. At time $t=0$ the capacitor is charged to a preset voltage by the computer. This voltage then decays exponentially. At time t_1, say, it has fallen to the value of the voltage across the monitor load. At this point a high frequency clock counter is started, to be stopped at time t_2 when the capacitor voltage has decayed further to the value across the load of the measurement photomultiplier. If with clear plate in the measuring beam the light intensity level is the same on each photomultiplier then the density of the photographic image is proportional to $t_2 - t_1$, *i.e.* to the number held in the clock register.

This can be read by the computer, at intervals appropriate to the plate measuring mode and recorded along with the coordinate data on magnetic tape. After each measurement cycle the capacitor is charged up to the reference voltage level and the clock counter reset to zero.

MECHANICAL SYSTEM

Basic Construction

The mechanical design of the microdensitometer embodies a general-purpose measuring engine of very high precision, which has been developed to provide the basis for a varied range of scientific instruments.

The basic engine provides two axes of servo-controlled motion to a high accuracy in both positioning and constant-velocity modes.

Each axis is independently mounted on the bed, an arrangement which provides tighter control over manufacturing and assembly tolerances than the more common pick-a-back configuration. The longer axis (X), with a travel of 300 mm, is in the form of a table with a rectangular hole, carrying suitable plateholders. The shorter axis (Y) with a travel of 150 mm, is in the form of a symmetrical gantry bridging the X table and carrying the main optical system, with an underarm passing beneath the X table and carrying the subsidiary optical system.

The two carriages and the machine bed are made of spheroidal grained cast iron, suitably ribbed and stiffened. They are carefully annealed and stabilized before initial machining, and again before final machining, in order to minimize the possibility of distortion during the life of the instrument. The weight of the bed is supported at three points only, to avoid distortion during final machining and subsequent transport and use.

Anti-vibration mounts are fitted between the machine bed and the supporting plinth, to provide isolation from seismic disturbances.

In order to meet the very exacting requirements of positional repeatability, it is essential that indeterminate friction forces on the carriages be kept to a minimum. Furthermore, since during operation the carriages are not subject to fluctuating forces (as they would be in the case of a machine tool) the requirements for stiffness of the machine structure and guideways are not exceptionally stringent. The combination of these two considerations leads to the choice of air bearing guide-ways.

The air bearing design employed is based on the work of Wunsch (1969) at the National Engineering Laboratories.

Careful attention to the disposition of critical components has produced an extremely high standard of metrological performance. The use of air bearings is of considerable benefit in this respect, in view of the purity of constraint which can be achieved with a planar bearing configuration.

The layout also takes into account such dynamical considerations as the need to have the applied forces in line with the centre of gravity for each carriage, in order to minimize transient orientational errors during stepping.

Mechanism of Guide-way Constraints

The basic elements of the planar air bearings employed consist of a precision flat (normally attached to the stationary member) and a bearing pad (normally attached to the moving member and supplied with air by a flexible pipe). Such an arrangement provides a pure planar constraint to the motion of the pad. In other words, motion of the pad in a plane parallel to the flat produces no reaction forces from the bearing system; motion perpendicular to this plane is associated with a restoring force directly opposing the motion and linear for small excursions. Alternatively a component of applied force perpendicular to the plane produces a corresponding deflection in the same direction (a typical compliance being of the order of 1 micron per kg).

Pursuing this simplified concept of the mechanism of constraint a little further, one can say that a *single* pad as described provides constraint only for *translational* motion in a single direction; very poor constraint is provided for *orientational* motion about axes lying in the plane, and no constraint at all for rotation about an axis perpendicular to the plane.

The necessary system of constraints required for the control of machine motion can be built up by the use of a number of planar constraint elements of the type discussed above. A plane of motion for a carriage can be defined by three elements (mutually parallel) and a line of motion within this plane can then be defined by a further two elements (perpendicular to the first set and parallel to the required line). In such a configuration the orientational stiffness of constraint depends on the product of element (translational) stiffness and span between pads, whereas the overall translational stiffness does not depend (to the first order) on the span, but only on the sum of the stiffnesses of the individual elements involved.

Similar reasoning applies to the accuracy of motion obtainable with a given quality of flat. The orientational errors decrease in inverse proportion to the span, whereas the translational errors are determined by the mean for all the flats involved.

When a constraint is produced by a combination of elements, the effective point of application is at the centre of pressure of the group of pads involved.

The linear bearings used on the two machine axes are basically similar in layout. The weight of each carriage is supported on four single-sided air bearing pads, one at each corner; these run on horizontal flat ways on the machine bed, which define the plane of motion. Although pure kinematic requirements would call for the use of three support pads for each carriage, it is considered more important in this instance to make each carriage broadly symmetrical in the X and Y directions, and this has led to the use of four pads in each case.

The line of motion within this plane is defined by two double-sided air bearing pads, one at each end of the carriage, running in precision channel-section guide rails fixed to the machine bed. The rails are adjustable to enable fine setting of the orthogonality of the two axes.

Disposition of Constraints

The departures from ideal linear motion for each carriage can be considered as made up from two quite separate classes of contribution: orientational and translational. Although this point seems obvious once stated, its implications are not in fact widely appreciated, as evidenced by the common practice of specifying machine accuracy solely in terms of autocollimator measurements, *i.e.* purely orientational data.

In general, machines with complicated configurations of guide-way (*e.g.* multiple ball bearings in vee-and-flat tracks) do not lend themselves readily to an insight of the problem in these terms. However a machine whose motions are defined by a number of planar constraints is not only more amenable to interpretation; more important, it provides the designer with the opportunity of putting these constraints to the best use. Once the mechanism is recognized through which the errors are controlled by the constraints, a layout can be specified such that each constraint is applied at the most suitable location. Due attention to this aspect can ensure that orientational errors of machine motion do not give rise to positional errors at the working point.

A full description of the departure from linear motion requires recognition of these two classes of measurement:

(*a*) ORIENTATIONAL, changes of angle between fixed and moving members. These can be detected by autocollimator techniques.

(*b*) TRANSLATIONAL, motions perpendicular to the operating travel. These can be detected by relative movement between a reference straight-edge on one member and a probe on the other.

In the case of the measuring transducer the requirements for siting to minimize errors appear to have been widely understood for some time. The name of the eminent German physicist Abbé is usually associated with the principle that the line of action of the transducer should pass through the working point, in the plane of the work-piece. It is somewhat surprising that the extension of the concept to cover the siting of guideways has been largely neglected.

Let us consider first the steering guideway system on, say, the Y carriage. An imperfect understanding of the "Abbé principle" might lead one to suggest that the steering rail should be, like the measuring transducer, positioned on a line through the working point; of necessity this implies that it would have to be displaced along the travel direction (to avoid obstruction of the optical path at the working point). However, a closer scrutiny reveals this to be a most unsatisfactory layout.

The Y carriage steering way provides essentially the constraint which locates the Y carriage in the X direction. This locating action is fully effective only at the point of application of the constraint (the centre of pressure, midway between the two steering pads). Other parts of the carriage which are offset some distance along the travel direction from this point will have the locating action degraded by any orientational errors which occur, the positional error being the product of offset distance and angular error. An offset distance along the direction of the constraint would not, however. lead to any first-order error in that direction.

The principle may be stated in more general terms as follows:

For a planar constraint system, a line drawn through the point of application (centre of pressure of pads) along the direction of the constraint should pass through the working point.

Applying these terms to the example of the Y steering ways leads to a recommendation that the rail should be alongside rather than at one end of the carriage, and the pads on the carriage should be equidistant along the travel direction with respect to the working point (*i.e.* the optical axis).

It should be emphasized that this approach does not claim the elimination of all errors. The positional inaccuracy at the working point must contain in any case the contribution from the translational errors of the guideways. However, by due attention to detail, the contribution from the orientational errors can be minimized or in most cases eliminated.

ELECTRONIC SYSTEM

Sequence Control

The instrument incorporates a PDP 8-I computer to provide flexible direct control of the operating sequence, positioning and data output.

A Teletype ASR 33 is included to handle input and output on punched tape, with black copy in each case. The primary role of this is the input of computer programs; as an output device it is appropriate only for small quantities of data or intermediate program information.

The normal flow of output from the automatic measuring sequence is handled by an incremental magnetic tape deck producing tapes in I.B.M. compatible format. An analogue chart recorder is also included for monitoring purposes.

The basic operating programs supplied with the equipment provide for a setting-up routine under manual control, followed by automatic scanning of spectra and background in a simple sequence.

The preliminary setting-up procedure includes:

(*a*) Orientation of plate or film holders.

(*b*) Setting of datum on both axes.

(*c*) Delineation of areas to be scanned (including curved paths for interpolation as necessary).

(*d*) Inspection for plate blemishes, and identification of areas to be rejected as necessary.

A typical example is the case of a plate carrying a stellar spectrum flanked on each side by reference spectra. Background measurements are required from two lanes flanking the reference spectra, giving a total of five lanes.

In the setting-up procedure the operator delineates the spectra and background lanes by positioning each end in turn beneath the optical axis, using the visual monitoring system in conjunction with a manual control panel to produce a punched tape from the computer giving a list of salient coordinates and mode instructions.

For spectra which lie along a curved path, each spectrum is delineated by logging a suitable number of points along the path. The computer program subsequently interpolates a straight line between each pair of adjacent points. Areas to be rejected are logged in a similar fashion.

In the automatic mode the intermediate punched tape information is used to control the system. Automatic measurement in its simplest form for such a plate consists of traversing each background

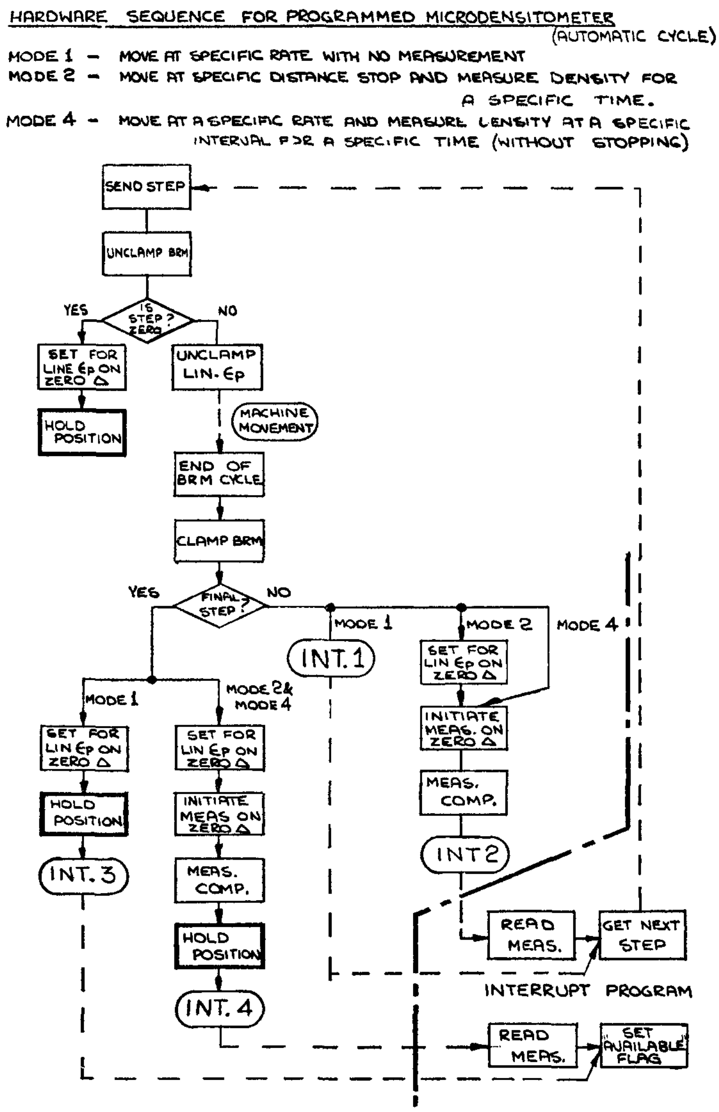


Fig. 4

lane and spectrum path in turn. Density readings at uniform intervals of traverse are transferred to the output magnetic tape. The interval need not be the same for all five scans. This form of scan may be performed either by stepping to each location and stopping during the density measurement or by continuous constant-velocity movement of the X axis with measurement whilst in motion.

The full potentialities of a computer-controlled densitometer extend, of course, far beyond such a basic scanning sequence. For example, it may be desirable to perform data reduction before transferring the density readings to the output tape. Alternatively there may be a requirement for an abbreviated scanning routine which examines only certain selected portions of the spectra in detail. It is considered, however, that the development of such special programs is best carried out by the scientific user rather than the equipment manufacturer.

A flow diagram for the various sequences is shown in Figure 4. The computer is responsible for

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setting up the modes from previously specified information and in the general case these modes may be changed at any time.

The hardware controls the data flow in the computer by means of the interrupt program. Typically the computer is reading or writing data and calculating its next move while the table is moving on its current operation. The interrupt program has been organized on the basis that when the table requires new information this takes precedence over any other operation. Results from the density counter are read while the table is moving to its new position.

Under manual control, each of the buttons gains immediate access for its function and during manual traverse the position counter is read into the computer every 10 millisec. This information is used to update the visual position display.

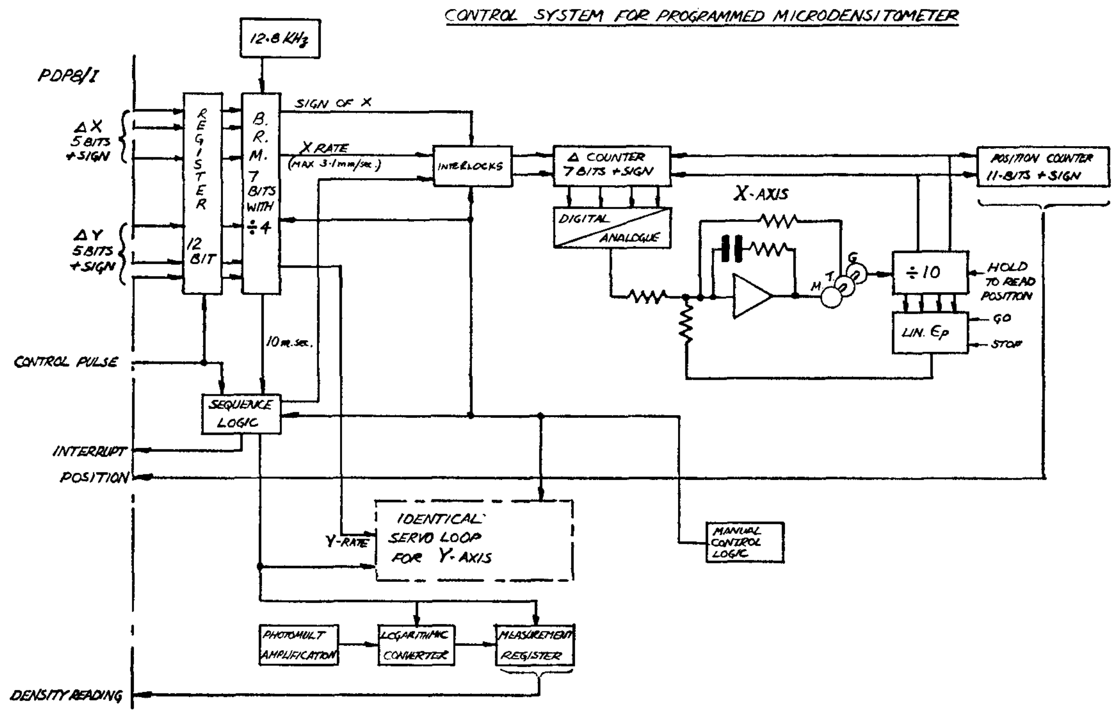

Fig. 5

Position Control

The X axis control loop is shown schematically in Figure 5. The Y axis loop is identical. Each axis of the table is controlled by a Type 1 position servo loop updated at regular intervals of 10 millisec from the computer.

At the end of a time interval, the hardware generates an interrupt which causes the computer to pause in its current task and send out distance increments ΔX and ΔY. These increments may vary from zero to 31 bits, (1 bit = 1 micron) and define either positive or negative movement.

The increments are fed to a binary rate multiplier which in turn feeds the corresponding number of pulses, spread equally over the time interval, into the position difference counter. The other input to this counter is fed by pulses derived from movement of the transducer attached to the table.

The output of the difference counter is converted into an analogue error voltage by means of the 8 bit digital to analogue converter whose output is shaped to give a double overshoot response and hence rapid settling. Since any departure of the difference counter from zero gives an error in position, the table will move in a direction which cancels the error and, in the steady state, with a rate which is equal to the rate of the incoming pulses.

Under dynamic conditions, this position loop is backed up by a tacho loop fed from the output. In order that the dynamic performance of the table be optimized, the transfer function of the amplifier is shaped by normal PID feedback and its output is pulse-width modulated to overcome the effects of stiction.

In order to achieve a high degree of position repeatability of the table, a subsidiary position loop is switched in for small error. This is indicated in the diagram as "LIN $\Sigma\rho$".

SUMMARY OF SPECIFICATION

Working travel: 200 × 150 mm.
Digital resolution: 1 micron.
Minimum step size: 1 micron.
Repeatability of X or Y setting: ±0.2 micron.
Orthogonality of X and Y axes: Within 3 sec of arc.
Absolute positional accuracy: ±2 micron over full travel.
Maximum traverse speed: 10 mm/sec.
Time for stepping, setting and measurement on steps of 25 microns: 50 millisec approx.
Density measurement range: D = 0.1 to D = 3.0.
Density measurement accuracy: D = 0.005.

As an indication of the performance capability of the machine, Figure 6 shows the accuracy of carriage motion measured for both axes. Figure 7 shows the repeatability of the position servo, tested on a prototype machine of similar dynamic characteristics.

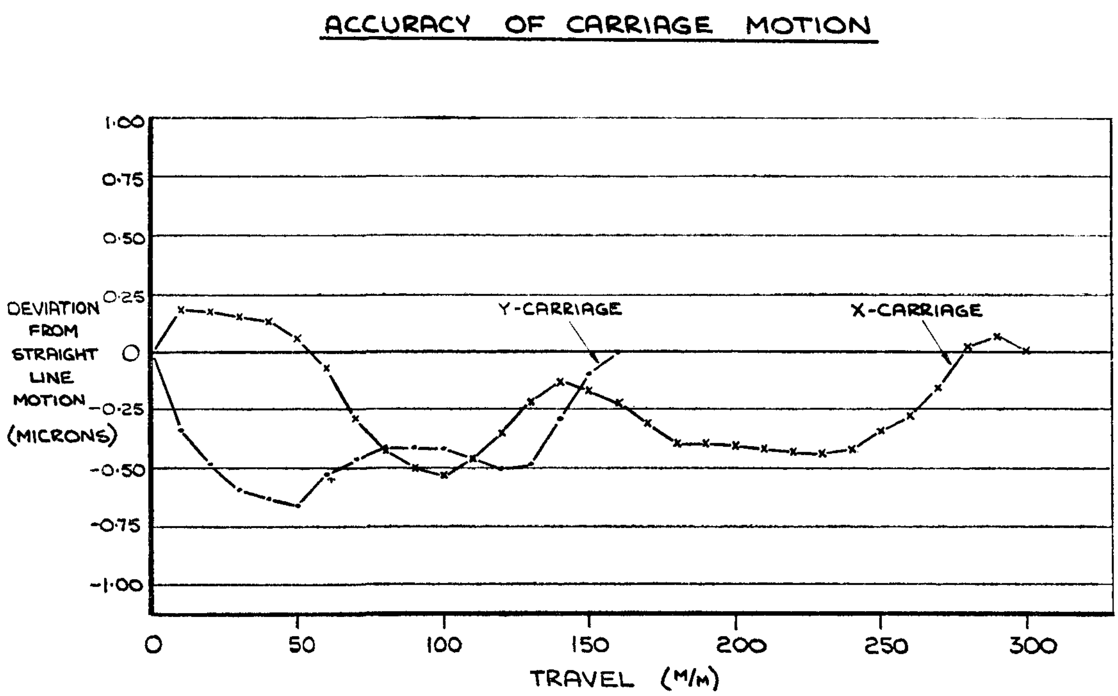

Fig. 6

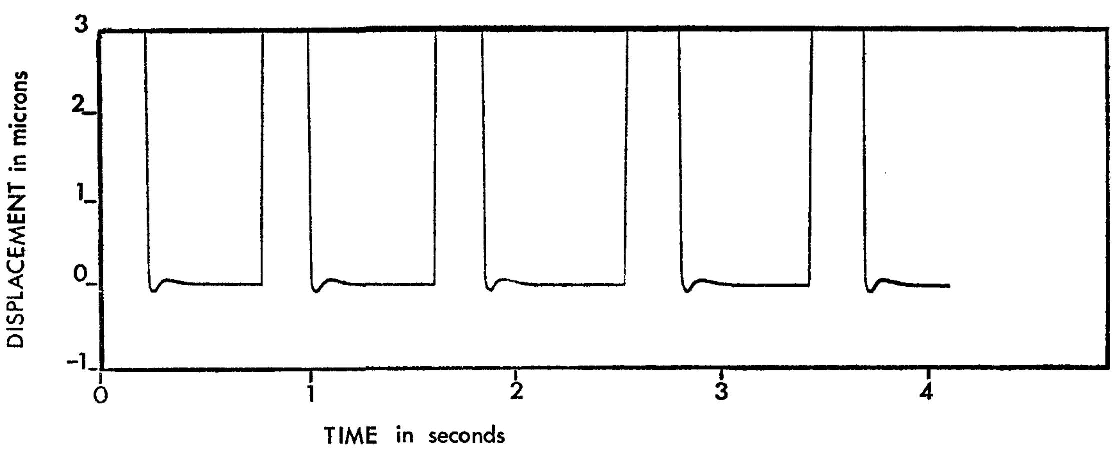

Fig. 7

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DISCUSSION

A. A. Hoag: The cycle time is given as 50 ms for each 25 μm step. Is this time independent of the resolution of the measurement, or does it decrease as you go to smaller steps?

R. Parks: The figure quoted was just one example. For smaller steps it would not shorten significantly because the machine settling time is quite an important proportion of the available 50 ms, but for longer steps it will lengthen a bit but not too much. The machine settling time is of the order of 20–30 ms, and maximum controlled traverse rate 2.5 mm per sec.

A. A. Hoag: What is the shortest step?

R. Parks: The short answer to that is that you would not use the mode of stepping, stopping and measuring for shortest steps, but you would use the continuous traverse and measure on the fly. At 1 mm/sec traverse rate you can perform the density measurement in 1ms and 1 μm of travel, which is a much faster way to operate if you're interested in closely-spaced measurements. The shortest step is 1 μm.

C. L. Stephens: What is the time for the computer to read in the density measurement; is that the limiting factor?

R. Parks: 1 ms is the time for the hardware to perform the comparison and counting to define a density number; after that the standard computer times to gather and assemble onto magnetic tape are shorter than 1 ms per observation.

P. Gillingham: Can you enlarge on your comment that the single-slit system was chosen to give less scattered light, since that would appear to be an advantage of the double-slit system?

R. Parks: We realize that there are two strongly opposed schools of thought on this subject. The balance of the argument swings in favour of a single-slit system when very narrow slit-widths (*e.g.* 5 μm) are required. The single-slit system also involves fewer air-to-glass surfaces in the light path, giving a useful reduction in light scatter.

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