Analysis of a photographic–vidicon camera method of LEED intensity measurements

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Low-energy electron diffraction (LEED) has great need for a quick and efficient means of making intensity measurements (e.g., in studying reactive surfaces which quickly degrade, and in handling the enormous amounts of data needed for data averaging). The photographic–vidicon camera method fills this need. This paper describes a system and procedure for this method. We have pointed out advantages of this method over other methods of LEED intensity data collection and analysis, and have included comments on the advantages of our experimental system over other systems using this method. General properties of the photographic and vicdicon system are analyzed as well as specific tests done on the method. Estimates of probable error in spot intensity measurements due to numerous effects have been analyzed and I–V curves reduced from raw photographic data are compared. It is hoped that the description, comments, and analysis will facilitate the incorporation of the photographic–vidicon method of LEED analysis into research programs.

INTRODUCTION

Low-energy electron diffraction (LEED) is now realizing its potential as a tool for surface structure analysis.[1] Although electron diffraction from surfaces was first observed in 1927, its development as a surface structural analysis tool required the attainment of ultrahigh vacuum for maintenance of surface conditions and the development of the theoretical understanding and calculational techniques needed to describe the strong electron–atom interactions which make the low-energy electrons surface sensitive.

Surface structure analysis requires the comparison of intensity profiles [i.e., $I(E)$ or I–V curves] obtained experimentally with those calculated for structural models. Presently there are two chief methods used for this surface structural analysis. Dynamical calculations can be compared to individual $I(E)$ curves[2] or kinematic calculations can be compared to averages at constant momentum transfer of experimental curves.[3] Each method has its advantages and disadvantages and both have been applied successfully to a variety of systems, from simple clean metals[4] to overlayer systems.[5] The latter method has also been applied to compound semiconductors[6] and to extensively reconstructed surfaces.[7]

Presently, most intensity data are measured either with a Faraday-cup collector system or with a calibrated telephotometer-fluorescent screen system. Both systems are available commercially (e.g., Varian for Faraday cup or fluorescent screen, Gamma Scientific for telephotometer). Both methods suffer the disadvantage of long, tedious data collection time which allows the possibility of surface degradation when studying reactive systems, and which greatly burdens the extensive data collection needed for the averaging method.

The desirability of shorter data acquisition time is frequently stressed[1,8] and recently a number of experimental developments have produced a reduction in this time. Stair, Kaminska, Kesmodel, and Somorjai[9] have developed a procedure of photographing the diffraction spots on the fluorescent screen of a display type apparatus and then scanning the negative with a mechanically driven digital-output microdensitometer to obtain a digital map of intensities from which peaks are found and integrated. The computer outputs a listing of spots by location and intensities for each frame. The total process takes about 20 min per frame.[10] In order to obtain an intensity profile one must scan the output for each frame to select the appropriate spot and intensity. Although the analysis required for an intensity profile is long and tedious, the actual data collection time is short, an exposure of 1 s per frame or about 10 min for an entire spectrum of a few hundred eV energy range. The photographic method has the advantages of recording all of the diffraction beams simultaneously and of producing a photographic hard copy of the data which may be analyzed and reanalyzed. The major disadvantage of the method of Stair *et al.* is the long and tedious analysis, after collection of the data, needed to obtain an intensity profile.

Another procedure, developed by Heilmann, Lang, Heinz, and Müller,[11] uses a vidicon camera in combination with a processing computer to scan the LEED screen directly. The spot of a particular diffraction beam may be selected and is then followed automatically as the energy of the incident beam is swept for an intensity profile. The intensity of the spot is computed and corrected for background in 0.5 s per point of the $I(E)$ curve. Compared to the photographic method, this method suffers the disadvantage of following only one beam at a time and of not producing a hard copy of the data. However, the use of a vidicon camera for intensity measurements is very encouraging. Recently, Lagally[12] has shown that the instrumental response function for a vidicon system which scans the fluorescent screen directly (Princeton Applied Research OMA combined with PDP-11 computer) is comparable to that of a Faraday-cup. Lagally has used the vidicon system to measure beam profiles [i.e., $I(\theta)$ curves] for structural analysis.

A successful combination of the above two methods has been developed by Frost, Mitchell, Shepherd, and Watson.[13] The LEED screen pattern is photographed and then the negative is scanned by a computer-controlled vidicon camera. This method has all of the advantages of the photographic method but with the increased speed, convenience, and efficiency of electronically scanning the film negatives. The purpose of this paper is to describe a similar system which has several advantages over the system of Frost *et al.*, and to report various tests and comments which will facilitate incorporation of such a system into a research program.

The system described in this paper is composed of commercially available components and is substantially less expensive than a complete digital scanning system such as that used by Frost *et al.* Compared to the latter system it is also quicker and more efficient. As with the latter system, it has the advantages of short data acquisition time, production of a hard copy of raw data, rapid reduction of raw data to intensity data, control of the reduction of data, and good resolution of measured intensities (for example, the method may be used for thermal studies and other line-shape dependent investigations).

I. EXPERIMENTAL SYSTEM AND PROCEDURE

The LEED system and electronics are from Varian and consist of an ultrahigh vacuum system, crystal manipulator, LEED gun and control, and 4-grid LEED optics. The LEED patterns displayed on the fluorescent screen are photographed through the 15.24-cm view port of the vacuum chamber. Standard Kodak Tri-X film and a 35-mm camera are used. The camera is an Olympus OM-1 with a 250-frame film back and motor drive, 85-mm lens and one 25-mm extension ring. The LEED patterns are photographed at a fixed exposure of 1 s at *f*/4. Calibration exposures of a Kodak No. 2 photographic step tablet are made at several times during the series of LEED pattern exposures. At each time three photographs of the step tablet are made at different exposures so that we are insured of an optimum calibration scale for each of the beams in the LEED pattern. (See description of software below.) The several sets of exposure are made in order to check (and to compensate for, if necessary) nonuniformity in the processing of the roll of film. The film is bulk processed at a commercial photo laboratory. Absolute calibration of intensity is not made, but the same relative scale can be obtained for each $I(E)$ curve since the standard exposure of the photographic step tablets can be used to account for roll-to-roll variation in processing.

The processed film is then analyzed with the computer-controlled vidicon system which digitizes the intensity on a scale from 0 to 255. The system (see Fig. 1) consists of a Hamamatsu C1000-00 vidicon camera and control unit, Hamamatsu M999 computer interface, 135-mm lens, extension ring, F to C mount adaptor for the vidicon camera, homemade light table, and Panasonic CCTV monitor. The vidicon camera is interfaced to a Data General Nova 3/12 computer with 32KW semiconductor memory and dual diskette drive and with a cathode ray display from Lear-Siegler. The interface is via an MDB Systems 4040 general purpose I/O board, with the 4041, 16-bit I/O registers, and the 4042, data channel connections, options. Excluding the cost of the minicomputer, the total cost is \$6530 (\$3500 for camera and control, \$2000 for interface unit, \$130 for camera lens and accessories, \$30 for light table, \$120 for TV monitor, and \$750 for the I/O board). This cost is to be compared with \$28 000 for the Computer Eye 108 image digitizer and recorder (Spatial Data Systems, Inc.) used by Frost *et al.* This commercial system, which also

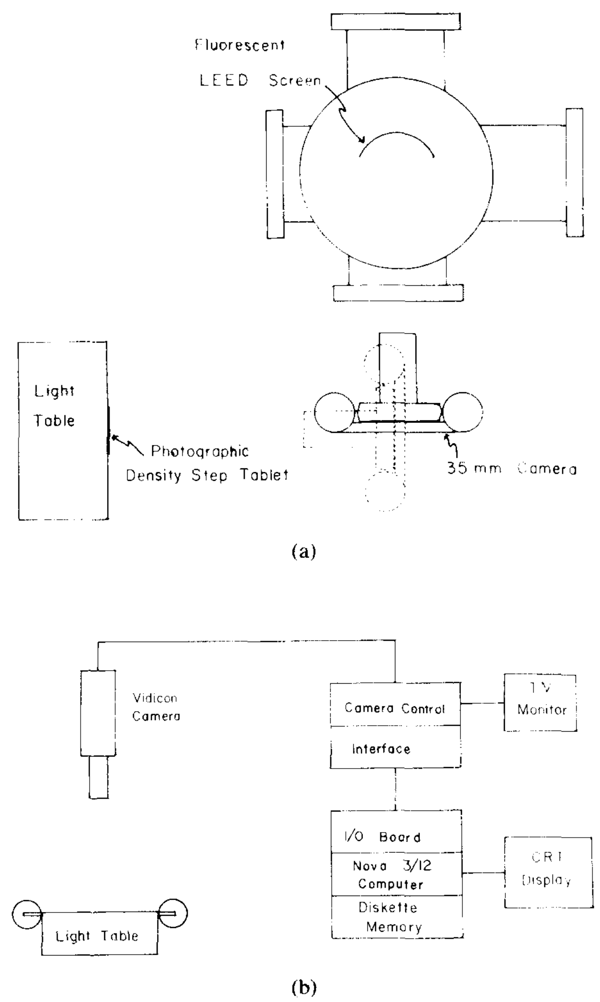

FIG. 1. (a) Schematic of the photographic system. (b) Schematic of the vidicon system.

needs an external computer, consists of camera and controller, digitizer, computer interface, TV display, light table, and joystick cursor.

The cost of our system also compares favorably with that of a spot photometer. Here a total cost of $7900 ($6530 for vidicon system and $1370 for 35-mm camera and accessories) is compared to $6000 for a telephotometer (Gamma Scientific). It should be noted that the vidicon system has the advantages of greater resolution, speed, and efficiency, and the production of a hard copy of raw data, which the photometer system does not.

The software for controlling the input and output of the TV camera and for determining the beam intensity were written in our laboratory. The TV control routines are written in assembler language and are based on a demonstration program supplied by Hamamatsu. There are four TV control routines, which open and close the TV interface, set a vertical line on the monitor, and input intensity data from one vertical line of the vidicon camera field. The film scan program (see Appendix) which determines the beam intensity is written in FORTRAN and calls the TV control programs. Although FORTRAN is used, a lower level language could be used if necessitated by computer size.

After initializing parameters in the program, a bias calibration (see below) is made and the sets of calibration exposures of the density step tablet are scanned. The calibration scales are created by computing from the known optical densities the relative real intensity of each step and matching these real intensities with the corresponding intensities recorded by the vidicon for the negative exposure of the step tablet. One of the sets of calibration scales is chosen; the optimum calibration scale is one in which the linear portion of the scale contains the range of the particular beam being studied. The interactive FORTRAN program then locates a spot by allowing the operator to move a vertical line on the monitor until it crosses the desired spot. This gives the X coordinate; the computer then determines the Y coordinate by finding the minimum intensity on the negative (maximum real intensity) along the line. The program then records the average camera intensity for a number of iterations of the points in a square grid centered on the X, Y position already determined. The grid consists of either every other X line and 2 to 1 interlace for a 40×40 grid of points out of a total field of 512×512 points, or every fourth line and 1 to 1 interlace for a 20×20-grid of points out of a total field of 256×256 points. The program next converts these raw intensities to relative real intensities, using the density step data, for all of the points of the grid and locates the maximum in the grid and the half-maximum points (relative to the lowest value in the grid) in four directions from the maximum point. The spot intensity is then calculated as the sum of intensities from points about the maximum point and within twice the average half-maximum distance. A background correction is made using the intensities of points in an annulus outside of the radius of the spot. The corrected spot intensity is displayed on the CRT and recorded in a data file in the diskette memory.

The collection of data only in a 40×40 grid, rather than the quarter million intensities possible per frame, allows the data to be stored in core memory and greatly speeds the program. The total time needed for the analysis of one spot is 30 s. Once the spot intensity is computed, it is displayed on the CRT and stored on the diskette in a file which stores the intensities $I - B$ of up to 10 spots per frame for up to 125 frames, along with the electron gun potential V and incident gun current I_0 for each frame. In the present method, the electron gun potential and incident gun current are recorded at the time of exposure along with the frame number. These data are then input to the diskette file at the time of film analysis. A digital display system (LEDs and two mirrors) is being designed which will allow the gun potential and incident current to be recorded on each photographic frame. Another possibility is to record the incident current for one run and then use it for the remaining runs. The data input into the file are the angles of incidence for the entire run, and frame number, V, I_0 and the $(I - B)$s for each frame. These data can then be manipulated to give $(I - B)/I_0$ vs V or $(I - B)/I_0$ vs $S_\perp$.

II. ANALYSIS OF THE SYSTEM AND PROCEDURE

A. General considerations

In this section we will consider some general points concerned with film processing, the use of a vidicon system as a quantitative tool, the resolution of the system, and the effect of the grids on the diffraction beam spot.

Variation in film processing was mentioned above. Variation in a particular roll has not been a noticeable problem, as determined by comparing the several sets of step density tablet exposures in a roll of film. The software can make a linear correction for variation by linearly interpolating between sets of step tablet data. Variation from roll to roll can be accounted for since the exposures of the density step tablets are standardized.

The use of the vidicon camera for accurate analytical measurements requires both a bias and a shading calibration.[14] The bias is the digitized output of the camera when the camera lens is covered; it can be regarded as a dark current. Shading refers to the variation of the blank field, i.e., the light table without a negative. Both corrections can be made for each point in the field scanned although we use average values as explained and justified below. The bias correction is defined as

$$B(i) = \langle I_0(i) \rangle_t, \tag{1}$$

where $B(i)$ is the bias correction for the ith point in the field, $I_0(i)$ is the intensity for the ith point, with the camera lens covered, and $\langle \ldots \rangle_t$ is the time average (i.e., average over, typically five, iterations). The shading correction is defined as

$$S(i) = \frac{\langle \langle I_b(i) \rangle_t - B(i) \rangle_x}{\langle I_b(i) \rangle_t - B(i)}, \tag{2}$$

where $S(i)$ and $B(i)$ are the shading and bias corrections for the ith point, respectively, $I_b(i)$ is now the intensity, for the ith point, with the camera viewing a blank field, $\langle \ldots \rangle_t$ is the time average, and $\langle \ldots \rangle_x$ is the spatial average (i.e., average over i). The intensity data is corrected for bias and shading according to the formula

$$I(i) = S(i) \times [I_c(i) - B(i)], \quad (3)$$

where $I_c(i)$ is the measured camera intensity for the ith point with the camera viewing the negative.

Both bias and shading can have systematic and random error. The systematic error consists of a drift for all $B(i)$ or $S(i)$. The random error is the variation of individual $B(i)$ or $S(i)$ over the field. A drift of ± 1 intensity units in the bias will produce a change of about 5% in the integrated real intensity of a spot. This was checked by using the raw intensity measurements of the camera and working through the program's normalization and integration procedures. In our software procedure we actually use a spatial average of the bias,

$$B = \langle B(i) \rangle_x, \quad (4)$$

rather than the quarter million individual $B(i)$; this adds a fixed random error to the time varying random error (see below). A variation of ± 1 in $B(i)$ due to the total random variation across the field will produce a relative error approximately $1/\sqrt{N}$ times smaller than that due to a drift of ± 1 in B, where N is the number of points in a spot (typically N is about 20 for a 1 to 1 interlace). The $1/\sqrt{N}$ factor derives from the fact that the integrated real intensity is computed as the sum of $I(i)$ within the spot and the variation of these points is of the same relative size. If all of the $I(i)$ within the spot were of equal size, the factor would be $1/\sqrt{N}$ as seen from an argument similar to that used to calculate the standard deviation of a mean from the standard deviation in the individual measurements. Since the $I(i)$ are not equal but are of the same order of magnitude we expect a factor only slightly greater than $1/\sqrt{N}$.

The bias, or dark current, does drift slowly; however, the drift is small for small bias. Also, the smaller the bias, the smaller the random variation in the bias. By adjusting the TV camera target control (at some cost to spread of intensity values) so that the average bias B is less than 2, the drift in B is only a few tenths in an hour and the variation across the field is ± 1. Therefore, we expect a relative error due to each of about 2%; furthermore, the software allows the bias to be remeasured at any time so that the normalization data can be rescaled to correct for bias drift.

Drift in the shading factor is due to drift in the intensity of the light table which can be caused by variation in the line voltage to the light table. The line voltage was found to vary ± 1 V, producing a 1% change in the blank field intensity and so also a 1% change in the shading factor. For typical values of camera intensity for the spot this implies a variation of ± 1 intensity units and an error of less than 5% in the integrated real intensity. To improve on this, either a regulated power supply can be used for the light table, or voltage to the light table or the intensity of the light table can be continuously monitored and then compensated for via software.

Again an average shading factor (i.e., 1) is used. The random variation in the shading across the field is about 2% which implies a variation in camera intensity of ± 2 units for points in the spot. Using the argument for the effect of the variation in the bias given above, this implies a relative error of less than 3% in integrated real intensity of the spot. Thus we see that the relative error in the integrated real intensity due to drift of and variation about the means of the bias and shading is about 5%, and error due to drift can be compensated for to reduce it to 3%.

A factor related to the above is the number of iterations used to collect the data. Data from the field can be collected once or a number of times and averaged. As the number of iterations is increased the range of random variation decreased. This change is most noticeable in going from 1 to 5 iterations and is very slight in going from 5 to 10 iterations. We are arbitrarily using 5 iterations as standard (a number which does not greatly increase the time of analysis).

A third general consideration is the resolution of the photographic-vidicon system. In our present system with a 135-mm lens the image of the 12.70-cm fluorescent screen is resolved to better than 0.025 cm when using the 2 to 1 interlace. (A longer lens or zoom lens could be used to increase the resolution.) A telephotometer at 183 cm and an optical pick-up fiber with angle of acceptance of 6′ yields a linear resolution of 0.305 cm. Thus, the linear resolution of the vidicon camera is about 10 times better than that of the spot photometer. To compare with a Faraday cup we note that the resolution of 0.025 cm on the fluorescent screen corresponds to an angle of acceptance of 0.23° relative to the crystal. The commercial Faraday cup in the Varian system has apertures of 0.0508, 0.1016, or 0.1524 cm which correspond to angles of acceptance of 0.57°, 1.15°, or 2.72°. More accurate Faraday cups can yield angular resolution of 0.25°.[15] Thus, the resolution of vidicon system is comparable to the best available Faraday cup detector research systems. (The curved surface of the fluorescent screen does cause a distortion of the peak shape as the spot moves away from the point on the screen at which the 35-mm camera is aimed.) In their review article of 1973,[15] Webb and Lagally mention that the finite size of the mesh in the retarding grids introduces a divergence in the diffracted electron beam, causing the angular width of the diffraction spot to be considerably larger than the angular width of the elastically scattered beam. They then argue that even though a spot photometer accepts light from only a small area, the signal is still characteristic of the integral over the spatial and angular extent of the electron beam. This is not exactly correct; rather the signal is convoluted with an instrumental response function[15] which depends on a number of factors, among which are energy resolution and mesh of the grids. A later study by Lagally,[12] comparing a Faraday cup with a vidicon camera scanning a fluorescent screen directly has found the instrumental response functions to be comparable. Lagally[12] has used the vidicon system to study the angular distribution of intensity.

Related to the question of resolution is the choice of background correction. Typically, in Faraday cup measurements it is assumed that only the peak is measured. Because of its lower resolution, the telephotometer measures the intensity of the peak and the surrounding area on the screen; a background correction usually involves measuring the intensity of an area adjacent to the spot. Software control of the vidicon scanning and processing of the intensity of the spot and surrounding area allows the experimenter to easily choose an appropriate correction. In our procedure we have chosen the spot radius to equal the full width at half maximum. If we assume a Gaussian shape for the peak our integral includes 94% of the peak intensity. Our background correction assumes that the peak is superimposed on the background. (We have not corrected for the 6% of the Gaussian peak which is included in the background annulus.)

It should be noted that our background correction is made in terms of intensity, not in terms of density as done by Frost *et al.*[13] The intensity background correction accounts for the brightness surrounding the spot on the fluorescent LEED screen. A density background correction accounts for the inherent opacity of the film negative and this correction is made automatically by our method of normalization (where opacity of negative image of the step tablet is compared to that of the spot image). The normalized intensities of the 40 × 40 grid are real relative intensities.

Actually our definition of the spot size and background correction is quite arbitrary. The diffraction peak is nearly Lorentzian in shape, with the wings associated with thermal diffuse scattering and becoming more prominent at higher temperatures.[16] In any case, one can choose the type of correction one wishes to make, and in fact, the hard copy of the raw intensity data even allows one to change one's mind.

A final consideration is the effect of the grids on the transmission of light. Legg, Prutton, and Kinniburgh[17] have derived and experimentally verified an expression for the ratio of the measured spot intensity to the actual spot intensity. The ratio decreases as the spot moves from the center of the screen to the edge. In the photographic–vidicon method the 35-mm camera–fluorescent screen distance is much shorter than the telephotometer–screen distance and so the intensity ratio is slightly larger for the former method. Although the correction is very slight in most cases,[18] the effect could be accounted for in the software data treatment. (This effect could be eliminated entirely by viewing the fluorescent screen from the convex side of the fluorescent screen, as in the LEED system described by De Bersuder.[19])

B. Specific considerations

We will now look at test results specific to the photographic-vidicon system and procedure described above. The tests all use the film scan program, whereas the results of the previous section used only the intensity output of the camera system. Two general types of tests were made: tests in which one spot intensity was measured under various conditions and tests in which a complete spectrum was taken.

The tests on one spot all involved measuring the intensity of the spot five or ten times, and then calculating the mean intensity $\bar{I}$, the sample standard deviation,

$$S_I = \left(\frac{1}{N-1}\sum_N (\bar{I} - I_i)^2\right)^{1/2}, \qquad (5)$$

and the ratio $S_I/\bar{I}$, which we will call the relative error. The results of these tests are given in Tables I and II. (To relate these results to those of Sec. II A, we note that the variation of Sec. II A is approximately two standard deviations.)

We will now analyze the results of Table I, considering first the variation in the intensity as a function of the number of iterations. If the standard deviation, $S_I(1)$, for one iteration is considered as the sample standard deviation, we would expect a standard deviation for N iterations, which is a mean of N values, to be

$$S_I(N) = S_I(1)/\sqrt{N}. \qquad (6)$$

We would then expect the standard deviation to decrease by 0.7, 0.4, and 0.3 compared to that for one iteration, as we increase the number of iterations to 2, 5, and 10, respectively. We do not see such a clear trend as this in the tests 1 through 4. However, we do see from results throughout the table that the relative error for five iterations is about 1% for bright spots and 4% for the dim spot (one tenth as bright). Also, we would only expect the relative error to decrease by a quarter (i.e., by a factor of 0.75) in going from 5 to 10 iterations.

To see how the results vary from day to day, we cannot take all of the tabulated results using 5 iterations, zero interlace, and step tablet data 2 because conditions were sometimes grossly different. However, by grouping those results which were taken under similar conditions, it was found that the relative variation was always less than 5%. This is larger than the 1% and 4% found above but is tolerable.

Increasing the resolution from a 20 × 20 to a 40 × 40 grid (compare tests 2 and 5) did seem to improve the relative error for dim spots but not for the bright spot. The time taken to analyze a spot was slightly more than doubled for 2 to 1 compared to 1 to 1 interlace. It may be noted that the spot intensities were less than the expected four times the 1 to 1 results, probably because of the more accurate integration of the edge of the spot.

The remaining tests show that extraneous factors do not affect the relative error in run to run but do affect the magnitude, and so consistent procedures should be

TABLE I. Results of specific tests.

Test[a]	Itera-tions	Inter-lace[b]	Step tablet[c]	Spot	$\bar{I} \pm S_I$	$S_I/\bar{I}$	Conditions other than standard
1	10	0	2	bright	409 ± 3	0.01	
				dim	29 ± 2	0.07	
2	5	0	2	bright	418 ± 5	0.01	
				dim	27 ± 1	0.04	
3	2	0	2	bright	421 ± 9	0.02	
				dim	27 ± 2.5	0.09	
4	1	0	2	bright	387 ± 5	0.01	
				dim	24 ± 2	0.09	
5	5	1	2	bright	1465 ± 21	0.01	
				dim	100 ± 2	0.02	
6	5	0	1	bright	84 ± 1	0.01	
				dim	—	—	
7	5	0	2	bright	376 ± 3	0.01	
				dim	21 ± 1.5	0.07	
8	5	0	3	bright	1158 ± 11	0.01	
				dim	195 ± 8	0.04	
9	5	0	2	bright	586 ± 4	0.01	no mask
				dim	106 ± 4	0.04	
10	5	0	2	bright	440 ± 4	0.01	masked
				dim	32 ± 2	0.05	
11	5	0	2	bright	291 ± 5	0.02	out of focus
				bright	357 ± 5	0.01	less out of focus
12	5	0	2	bright	410 ± 4	0.01	room lights on
				bright	466 ± 5	0.01	room lights out
13	5	0	2	bright	483 ± 2	0.004	position on monitor $Y = 52$,
				bright	442 ± 6	0.01	$Y = 130$, $Y = 178$; position on
				bright	404 ± 3	0.01	light table fixed in middle.
14	5	0	2	bright	456 ± 4	0.01	position on monitor fixed $Y = 130$;
				bright	442 ± 6	0.01	position on light table varied
				bright	445 ± 4	0.01	upper, middle, lower
15	5	0	2	bright	436 ± 5	0.01	position on monitor and light table
				bright	397 ± 5	0.01	varied; slide film on table $Y = 38$,
				bright	417 ± 11	0.03	$Y = 109$, $Y = 218$
16	5	0	2	bright	453 ± 4	0.01	line voltage to light table 122 v,
				bright	406 ± 2	0.004	126 v

[a] Data was not all taken at the same time nor in the order given; groupings for specific tests were taken at the same time.
[b] 1 refers to 2 to 1 and 0 refers to 1 to 1 interlace.
[c] 1 refers to an exposure of $f/4.0$ at 1/60 s, 2 to $f/5.6$ at 1/60 s, and 3 to $f/8.0$ at 1/60 s.

established. The test involving the mask consisted of allowing the vidicon camera to view the negative and bare light table at the edge of the negative and then masking the negative with a black frame so that only the negative was viewed. The vidicon camera and control measures a relative intensity scale based on the whole field

TABLE II. Intensities for tests 6, 7, and 8.

Wedge	Exposure	$\bar{I} \pm S_I$	Max I in spot	Min I in spot
1	$f/4.0$ at 1/60 s	84 ± 1	14	1.0
		—	1.0	1.0
2	$f/5.6$ at 1/60 s	376 ± 3	35	1.0
		21 ± 1.5	6	1.0
3	$f/8.0$ at 1/60 s	1158 ± 11	83	14
		195 ± 8	23	11

scanned and the use of the frame allows a consistent definition of this relative scale. The TV camera focus, room light conditions, and the light table intensity (i.e., the line voltage to it) should be fixed. The tests concerned with the position of the spot on the light table or on the monitor are perhaps surprising; however, the combined effect (test 15) shows a variation as a function of position of 5% (again, variation is approximately twice S_I).

Tests 6–8 test the effect of the choice of density step tablet exposure. The relative errors for the three wedges are all comparable. Since the three exposures represent a halving of the exposure we would expect a doubling of intensity, but we do not see this for the spot intensities nor for the maximum value of intensity in the spot (see Table II). This matter will be discussed below when we compare spectra taken with the different step tablet data.

Another comment before going on to the analysis of the spectra is that the radius of the spot was not critical. While collecting the data of the sets of ten measurements the radii used for individual measurements were noted. Although the radius varied in some sets, the integrated intensity of this spot did not.

The tests involving the intensity measurements for a complete intensity profile consist of measuring an I–V profile with the photographic–vidicon camera method and comparing it to the same I–V profile as measured by a telephotometer, and measuring an I–V profile from the same raw photographic data a number of times on different days and using the normalization data of different exposures of the density step tablet.

Figure 2 shows the comparison of the photographic–vidicon camera method and the telephotometer method. The profile is for the (11) beam of ZnTe(110) at normal incidence.[20] The telephotometer I–V profile is actually the average of 9 separate profiles all taken at normal incidence. Also, these data have been renormalized such that the 69-eV peak height is that of the corresponding peak of the vidicon run and then has been displaced 10 relative intensity units above the vidicon data. The agreement is excellent; even at 36 eV, where there is a discrepancy in peak height, the vidicon peak height does lie within the error bars of the average curve which are quite large at low energies.

Figure 3 shows three I–V curves superimposed in

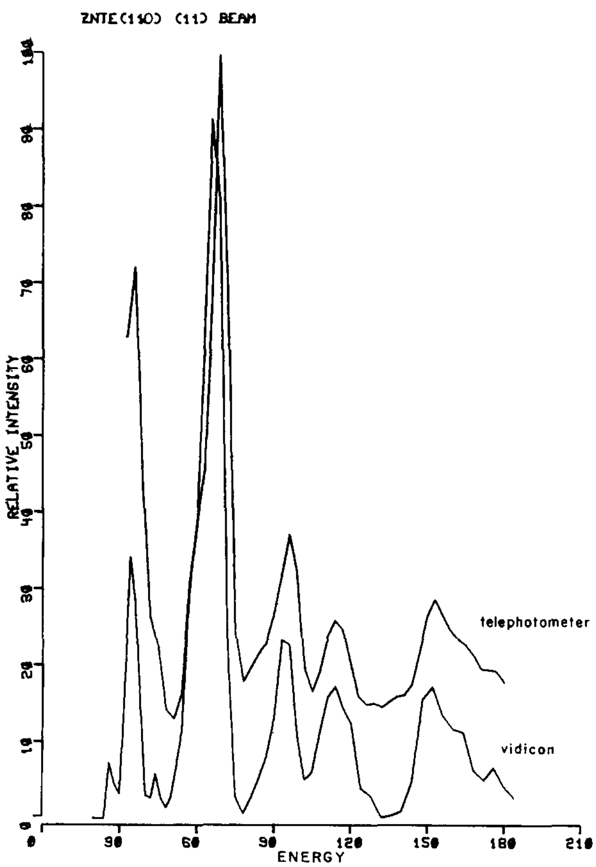

FIG. 2. Relative $(I - B)/I_0$ versus energy as measured by a telephotometer and by the photographic-vidicon camera method. ZnTe(110), (11) beam, normal incidence.

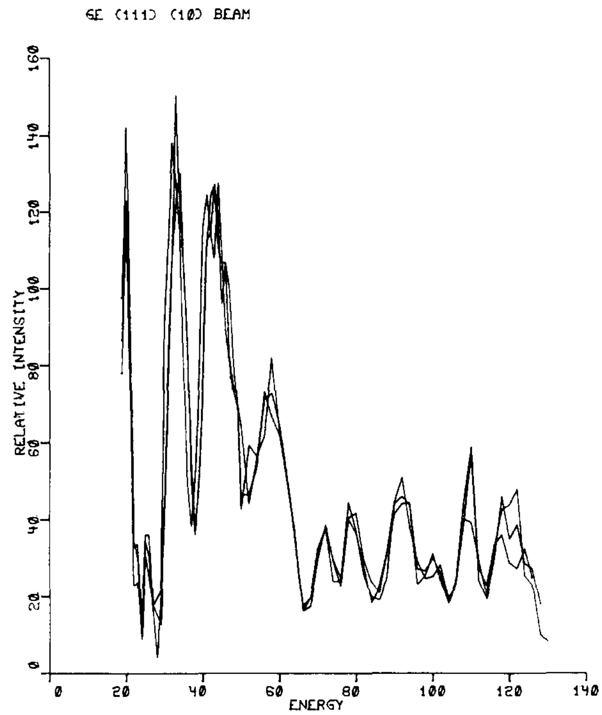

FIG. 3. Relative $(I - B)/I_0$ versus energy for three measurements of the same raw photographic data. (See text for further explanation.) Ge(111) – (2 × 8), (10) beam, normal incidence.

order to show the consistency of the results. The I–V profile measured is that of the (10) beam of Ge(111) – (2 × 8) at normal incidence.[20] Two curves were taken on one day using step tablet data 2 and 3 (2 refers to an exposure of $f/5.6$ for 1*s* and 3 refers to $f/8.0$ at 1*s*) and the third was taken on another day using step tablet data 2. The relative intensity scale for the curve using normalization data set 2 is scaled exactly one half of that using data set 3. (i.e., relative intensity = $(I - B)/I_0/50$ for set 2 and $(I - B)/I_0/100$ for set 3, where $I - B$ is background corrected intensity and I_0 is incident electron beam current in μA).

The 1 to 2 scaling for I–V curves using the different normalization data is very encouraging (and is at variance with the results of test 6, 7, and 8 of the single spot tests). This consistency allows the relative intensity scales to be adjusted linearly for differences in roll-to-roll film processing variation.

Two final comments should be made about I–V curve analysis and the normalization data. The first concerns the choice of the normalization data set to be used. In the above tests data sets 2 and 3 gave results but set 1 ($f/4.0$ at 1*s*) was overexposed and so the measured camera intensities for a point in the spot and a point in the background scaled to approximately the same relative real intensity. (See Fig. 4, which shows plots of the normalization data for the three exposures.) Typically, we have found that the I–V curve can be measured if the difference between the maximum real intensity in the spot and the background is greater than 5 relative intensity units for all of the frames. Also, the difference should not be so large as to be on the very flat region of the normalization curve (see Fig. 4), where small

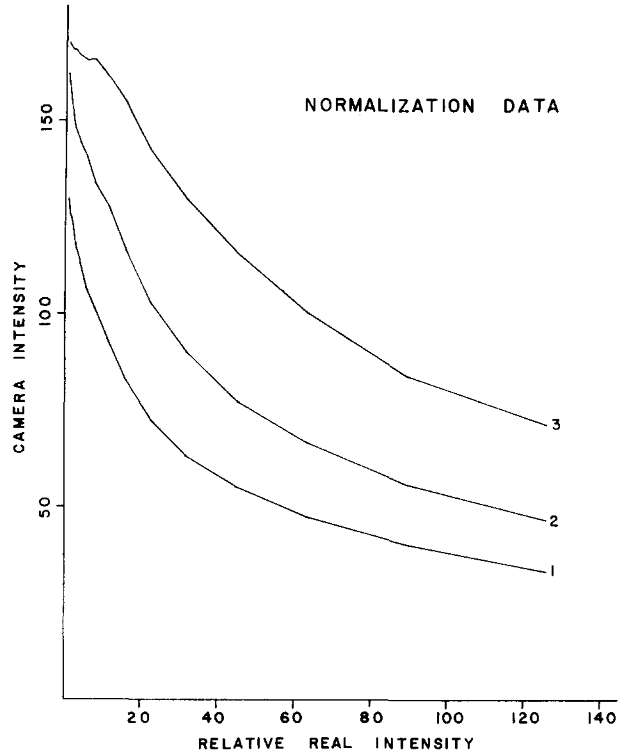

FIG. 4. Plot of normalization data. Relative real intensity versus camera intensity for three exposures of the density step tablet: (1) *f*/4.0 at 1 *s* (2) *f*/5.6 at 1 *s*, (3) *f*/8.0 at 1 *s*.

changes in camera intensity produce very large changes in real relative intensity. Whether this criterion is met can be checked by measuring a few typical spots along the film strip for a given normalization data set. If the program computes a reasonable intensity the data set is adequate. As an extra check, the program outputs on the CRT the maximum and minimum intensity in the 40 $\times$ 40 grid, along with the integrated spot intensity, and so the difference can be checked to see if it is greater than 5.

The second comment concerns reciprocity, which refers to the loss in sensitivity of photographic materials when exposures are made at very high or very low illuminances.[21] Both the photographic and vidicon systems can have reciprocity effects. Stair *et al.*[9] have shown that reciprocity is not a problem with the photographic method. Vidicon reciprocity is the cause of the bending over of the curve 3 (*f*/8.0 at 1*s*) of the normalization data plotted in Fig. 4. However, the agreement of the I–V curves of Fig. 3 shows that this reciprocity is not a problem. The reason for this is that the error produced affects only the background intensity corrections which are minor compared to the spot intensity when this normalization data set is used.

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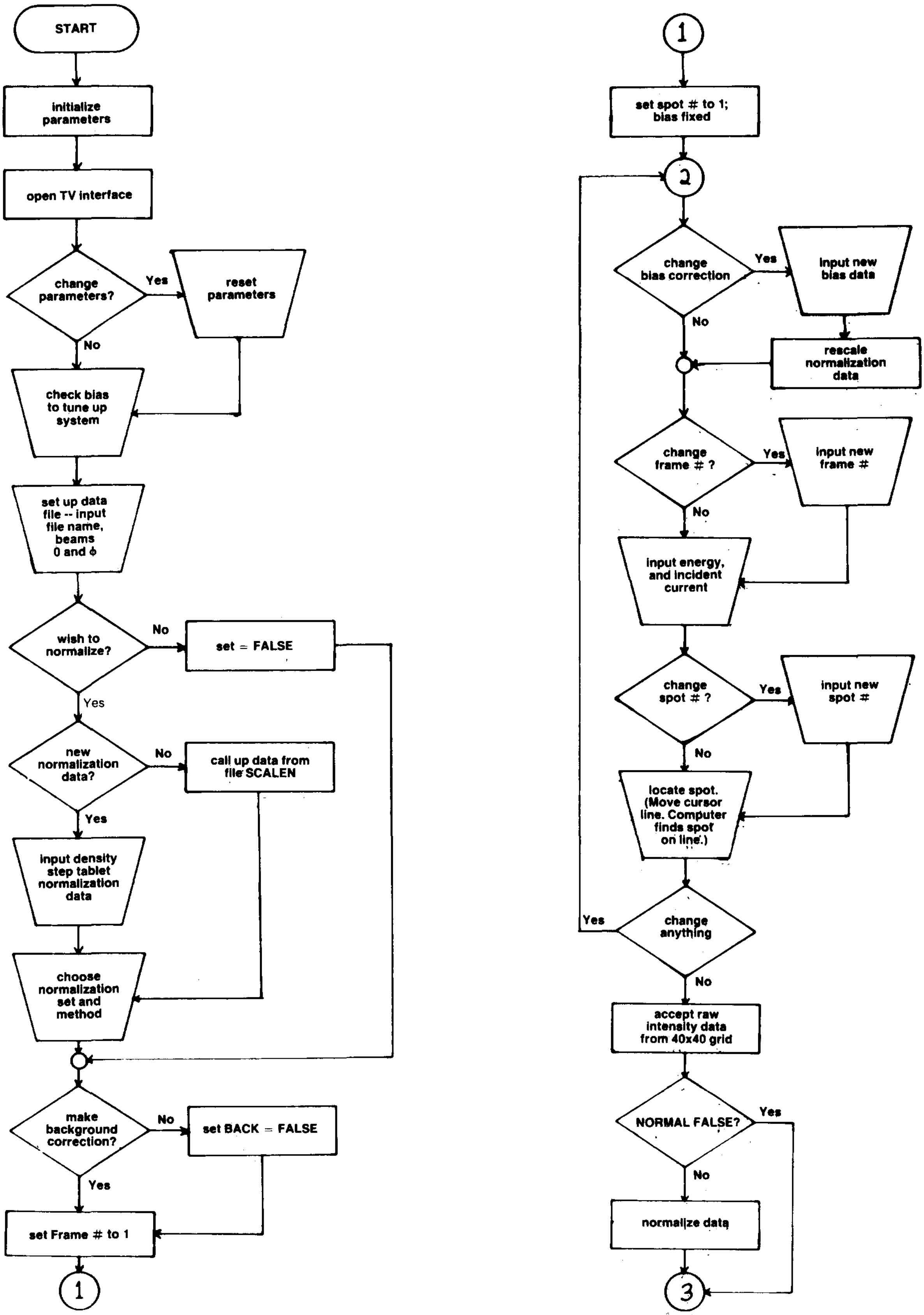
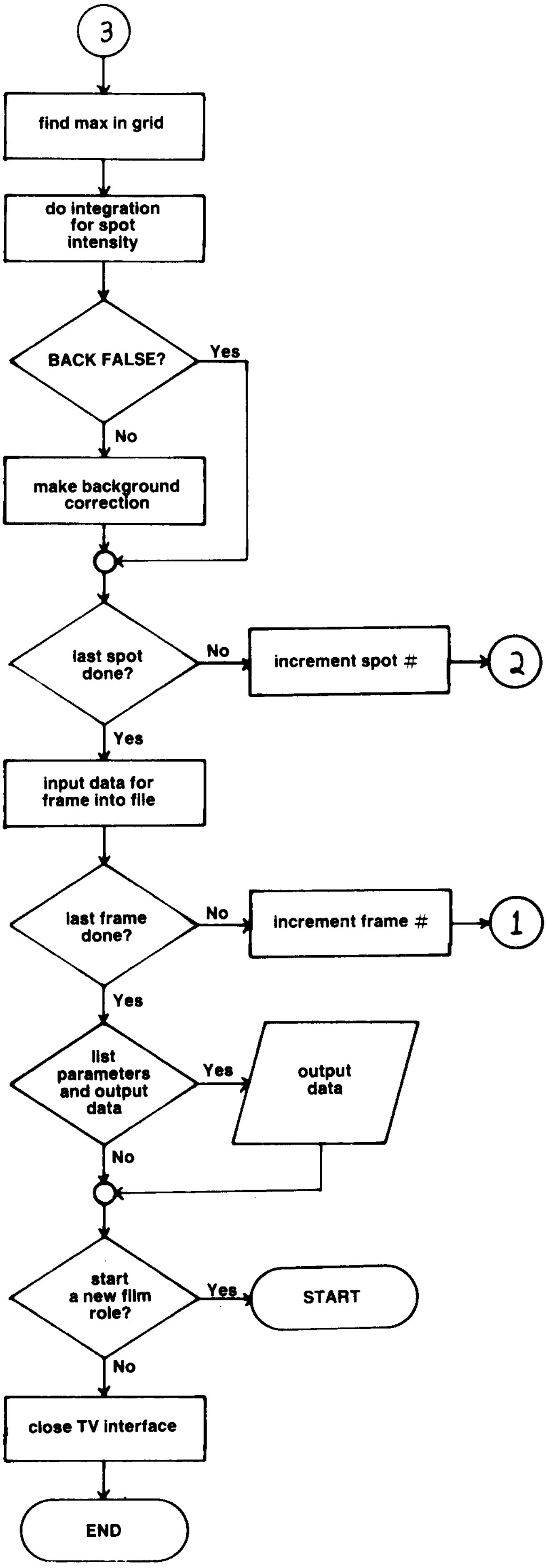
[1] J. B. Pendry, *Low Energy Electron Diffraction* (Academic, New York, 1974).
[2] F. Jona, Discuss. Faraday Soc. **60**, 210 (1975).
[3] T. C. Ngoc, M. G. Lagally, and M. B. Webb, Surf. Sci. **35**, 117 (1973).
[4] For example, Ni(100), (220), (111): J. E. Demuth, P. M. Marcus, and D. W. Jepsen, Phys. Rev. B **11**, 1460 (1975); Ag(111): M. G. Lagally, T. C. Ngoc, and M. B. Webb, Phys. Rev. Lett. **26**, 1557 (1971).
[5] For example, N on Mo(100): A. Ignatiev, F. Jona, D. W. Jepsen, and P. M. Marcus, Surf. Sci. **49**, 189 (1975); O on Cu(100): L. McDonnel, D. P. Woodruff, and K. A. R. Mitchell, Surf. Sci. **45**, 1 (1974).
[6] GaAs(110): A. Kahn, G. Cisneros, M. Bonn, P. Mark, and C. B. Duke, Surf. Sci. **71**, 387 (1978); A. Kahn, E. So, P. Mark, C. B. Duke, and R. J. Meyer, J. Vac. Sci. Technol. **15**, 1223 (1978).
[7] Si(100): T. D. Poppendiech, T. C. Ngoc, and M. B. Webb, Surf. Sci. **75**, 287 (1978).
[8] F. Jona, Surf. Sci. **68**, 204 (1977).
[9] P. C. Stair, G. J. Kaminska, L. L. Kesmodel, and G. A. Somorjai, Phys. Rev. B **11**, 623 (1975).
[10] P. C. Stair (private communication).
[11] P. Heilmann, E. Lang, K. Heinz, and K. Müller, Appl. Phys. **9**, 247 (1976).
[12] D. G. Welkie and M. G. Lagally, Bull. Am. Phys. Soc. **23**, 390 (1978); M. G. Lagally and D. G. Welkie, Bull. Am. Phys. Soc. **23**, 390 (1978).
[13] D. C. Frost, K. A. R. Mitchell, F. R. Shepherd, and P. R. Watson, J. Vac. Sci. Technol. **13**, 1196 (1976).
[14] J. I. McConnell, "C1000 Demonstration Program Manual," Hamamatsu System, Incorporated, Bedford, MA 01730 (1977).
[15] M. B. Webb and M. G. Lagally, Solid State Phys. **28**, 301 (1973).
[16] E. R. Jones, Ph.D. thesis, Univ. of Wisconsin, Madison, WI (1965) (unpublished).
[17] K. O. Legg, M. Prutton, and C. Kinniburgh, J. Phys. C **7**, 4236 (1974).
[18] W. N. Unertl and H. V. Thapliyal, J. Vac. Sci. Technol. **12**, 263 (1975).
[19] L. DeBersuder, Rev. Sci. Instrum. **45**, 1569 (1974).
[20] Peter Mark, Ed So, A. Kahn, and J.-L. Yeh, Dept. of Electrical Engineering, Princeton University provided the raw photographic data for the Ge(111) spectra and the raw photographic and the telephotometer data for the ZnTe(110) spectra.
[21] C. S. Williams and O. A. Becklund, *Optics: A Short Course for Engineers and Scientists*" (Wiley Interscience, New York, 1972).

Appendix

Flow chart of the software for the film analysis.




3
find max in grid
do integration for spot intensity
BACK FALSE?
Yes
No
make background correction
last spot done?
No
increment spot #
2
Yes
input data for frame into file
last frame done?
No
increment frame #
1
Yes
list parameters and output data
Yes
output data
No
start a new film role?
Yes
START
No
close TV interface
END