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ACQUISITION HARDWARE FOR IMAGING

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Abstract

In electron microscopy images can either be recorded in parallel (Transmission Electron Microscopy) or acquired as the variation in a signal as a probe is scanned over the specimen (Scanning Electron Microscopy). To extract the most information from an image requires that the best possible systems are used for acquiring image data. Ultimately, the limit to information capture is achieved when every electron from the scattering event of interest is recorded. The ideal system can be realised both for parallel recording with scientific grade CCD cameras, and for scanning microscopy with single electron counting electronics. The data rates from these different systems impose different constraints on the computer systems needed to acquire and display the incoming images.

Key Words: Electron microscopy, scanning, CCD camera, computer control, digitization, image processing, image acquistion.

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Introduction

The appeal of electron microscopy is, in part, due to the impact of images as opposed to strings of numbers or graphs. Now that powerful computers are available, images can be analysed in a quantitative manner. Microscope images in a conventional transmission microscope are recorded directly as the electron current distribution on a viewing screen or a photographic plate. Electron diffraction patterns can be viewed by focussing on the back focal plane of the objective lens. For the purposes of signal processing they can treated in the same way as images. Alternatively, in scanning microscopy, the image is formed by modulating the intensity of a display according to the strength of a specimen induced signal as a small probe is scanned in synchronism across the specimen. As electron beam damage is significant for all specimens but particularly for biological specimens, polymers and catalysts the ideal system would record each scattered electron that conveys significant information. At the highest magnifications it is also desirable that each picture element (pixel) is no larger than half the spatial resolution and that the picture size is sufficient to view the objects of interest. A direct link to a powerful computer system is also essential if images are to be analysed in a quantitative manner. When important information can be presented online to the microscopist it can significantly change the way experiments are performed. In the next sections the conventional acquisition systems for both conventional and scanning microscopy will be described with particular emphasis on how they compare to systems with ideal performance.

Transmission Microscopy

Traditionally, transmission microscope images have been viewed directly on fluorescent screens or recorded on photographic plate.

Neither method allows immediate online data processing and analysis. Considerable advances in quantitative electron microscopy have been made by digitising prerecorded electron micrographs.[4] Spot microdensitometers were originally used in which the intensity of a small beam passing through a negative is compared with a reference beam and the result digitised. Although densitometers were useful for small regions or spots in a diffraction pattern they were very slow in digitizing whole images. Recently devices based on 2 dimensional CCD (charge coupled device) cameras or scanning a 1 dimensional CCD array across an image have become more popular. The image can be scanned at the same resolution with the same intensity range as the densitometer but at higher speed and with more flexibility. Online processing of images became possible when TV cameras viewing a phosphor or scintillator were added to the microscope[12,28]. In the case of high voltage microscopes supplementary intensification has also been required. More recently slow scan CCD cameras have been used to record electron diffraction patterns[20,30] and it is now possible to capture images with single electron counting.

All image acquisition systems can be specified by common characteristics that relate to the range of intensities that be recorded, the spatial resolution of the recording device, the efficiency with which the system picks up a signal and the distortion the device introduces to the image.

The range of intensities that can be recorded is known as the dynamic range. TV cameras have a very low dynamic range, usually about 100. In practice the transfer curve relating recorded intensity to input intensity is non linear, and the linear part of the dynamic range (linearity being defined in terms of a percentage deviation from a straight line) is much less, typically about 20-50. Photographic film has a dynamic range that depends partly on developing conditions, but is usually about 1000. This is more than sufficient for images but is inadequate for many diffraction patterns where the intensity difference between the 000 beam and weak superlattice reflections can be between 1000 an 10000. Multiple exposures are therefore necessary to capture all the information. The dynamic range of a slow scan CCD camera is usually limited by the precision of the final analog to digital converter which is 16384 (14 bit) for a reasonable system.

The spatial resolution of the system can be specified in terms of the number of line pairs per mm but it is better to use the modulation transfer function (MTF). Given an object which has a complete range of spatial frequencies (white noise or in HREM an amorphous thin film) the modulation transfer function is defined as the ratio of the signal at a given spatial frequency divided by the signal at zero spatial frequency. It is not strictly necessary to measure the MTF from an object with a complete range of spatial frequencies. It can be measured from the response of a known object such as a straight edge. In the case of TV or CCD systems both the response of the phosphor or scintillator and the response of the camera give contributions to the MTF. The MTF can be used to define an effective picture element or pixel size by taking the inverse of the spatial frequency where the MTF has fallen to an arbitrary amount (usually 50%). When intensifiers are added to a system they result in further degradation of the MTF. Comparing systems loosely in terms of number of pixels per line the photographic plate has 3000 30μ pixels, the TV camera has 200 50μ pixels and the slow scan CCD can have 1024 pixels of size 20-25μ[3,21]. A modulation transfer function for a slow scan CCD camera is shown as Fig. 1.

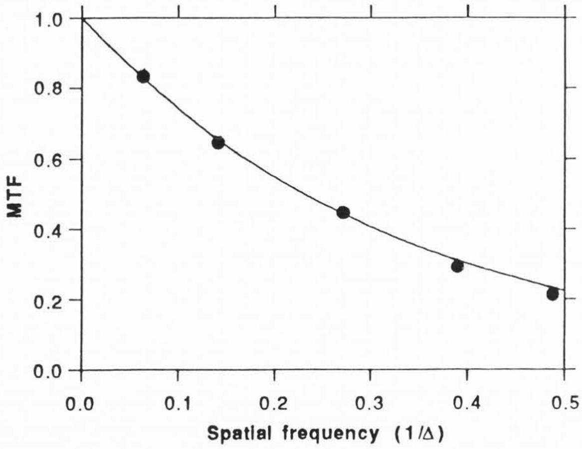


Figure 1 Modulation Transfer Function for a Gatan 679 slow scan CCD camera. The pixel size is Δ. Dots represent measurement, the solid line is an exponential fit through the measurements.

The efficiency with which a system picks up a signal is best defined in terms of the detector quantum efficiency (DQE) [11]. The strict definition is

$$DQE = \frac{SNR_{out}^2}{SNR_{in}^2} \qquad (1)$$

where SNR is the signal to noise ratio and is the standard deviation of the signal divided by the

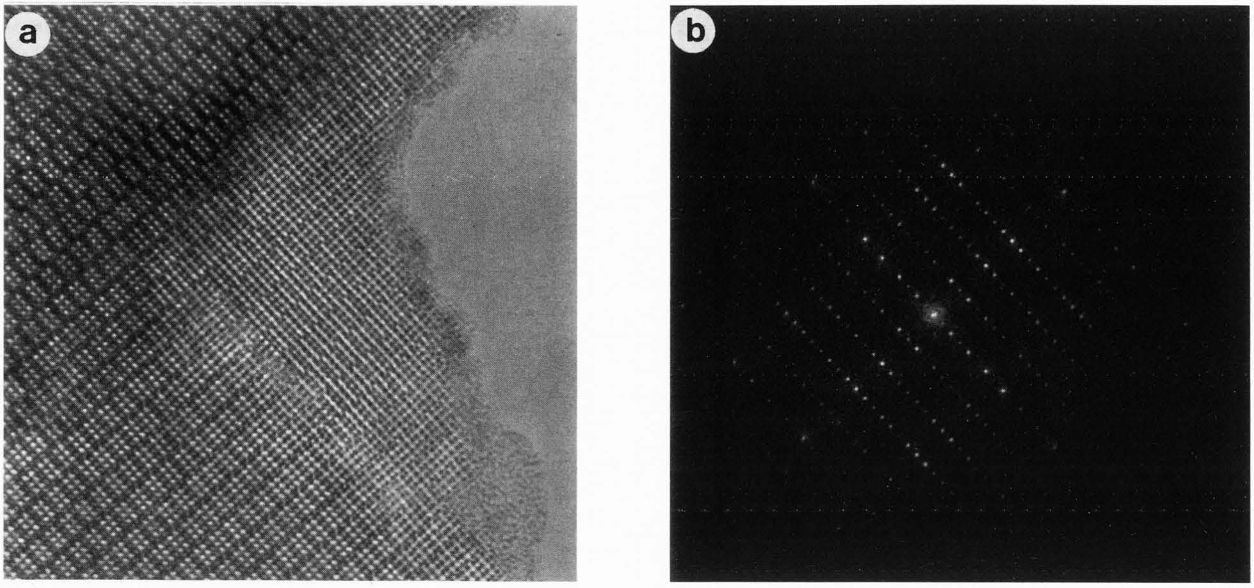


Figure 2(**a**) $Ti_2Nb_{10}O_{29}$ image captured using slow scan CCD camera; the individual blocks at top left are 10 Å x 14 Å. (**b**) Diffraction pattern obtained using slow scan CCD camera.

standard deviation of the noise. An ideal detector which records single electron events has a DQE of 1.0. This is true for slow scan CCD cameras and photographic plates which can have a DQE between 0.8 and 1.0 depending on developing conditions. The DQE of SIT (Silicon Intensified Target) tubes for electron counting is very dependent on the phosphor and optical coupling. Optimised systems can have a DQE of 0.6-0.9 though a value of 0.2 is more realistic for normal operation. ISIT (intensified SIT) tubes, which couple an intensifier with the SIT tube, are capable of single electron counting. As the phosphor or scintillator generates at least 10 -100 photons for a high energy incident electron the device does not need to meet the more challenging requirements for single photon counting (as in astronomical work).

The geometric distortion is specified as a percentage change of the length of the diagonal of the camera face. It is entirely negligible for slow scan CCD cameras or photographic film but can be 5% or more for electron tube TV cameras. The longer the TV camera tube the lower the geometric distortion.

The images from TV cameras or slow scan CCD cameras can only be displayed using a display monitor. For TV camera systems it is simple enough to connect a TV monitor or video recorder if the camera is giving out appropriate synchronization pulses. It is often advantageous to take the signal into a region of digital memory known as a frame buffer and then display the contents of this buffer. As video displays are unable to synchronize with a slow scan CCD camera it is essential to use a frame buffer. The frame buffer can also be accessed by a general purpose computer which allows for some image manipulation and storage on computer disk. For a TV system a frame buffer of 512x 512 1 byte (8 bit) pixels is sufficient. As TV cameras have a 4:3 aspect ratio it is often desirable to use a buffer 480 lines by 640 points taking account of the number of visible lines in the US (NTSC) standard. The pixels are square which is essential for operations involving 2 dimensional Fourier transforms. For a slow scan CCD system, or even a TV rate system with signal averaging, it would be better to use a 2byte (16 bit) buffer to accommodate the increased dynamic range.

From the point of view of the computer system and frame buffer the most important parameter is the rate at which the image is scanned from the image pickup device. TV rates are given by broadcast standards and correspond to one frame every 1/25 sec in Europe or every 1/30 sec in the United States. The number of lines also differs according to the two standards but in both cases interlacing is used in which the odd lines of a frame are scanned first and then the even lines are scanned. Although this gives an improvement for moving images it results in an annoying flicker for graphs and text which is why interlacing is never used in computer displays. Digitizing the TV line with 512 samples requires an approximate data rate of 10 Million pixels per second. Only a high speed flash converter can work at this rate, and generally these devices only digitize to 8 bits (256 levels). In practice, the signal to noise ratio would not justify any increase in digitization precision. The high data rate has consequences for the frame buffer design as normally cheap dynamic random access memories can not be accessed at these speeds. Special memory organizations have to be used in which a number of memory locations are accessed in parallel and then shifted out through a register. Memories with this capability included in the memory chip are called video RAMS. It is also important for the computer to share memory access cycles with the video input so that it can process the data during acquisition. The slow-scan CCD camera makes less stringent demands on the frame buffer and the computer system. Although the CCD chip can output data at quite high rates (up to a few million samples a second) the accumulation time is determined by the appropriate signal to noise ratio and can vary from a few milliseconds to minutes. The controlling factor is the digitization rate of converters of suitable precision. For 14 or 16 bit conversion successive approximation converters must be used and these could take about 10 μsecs per digitization. This gives a minimum image acquisition time of 2.5 secs for a 512x512 image or 10secs for a 1024x1024 image. It might be more convenient to have a lower precision 12 bit converter which takes about 1 to 2 μsec per pixel. In this case about 4 512x512 images can then be acquired every second, which is still barely sufficient for interactive manipulations such as specimen translation, focussing and stigmation. It might be necessary to combine the slow scan CCD camera with a TV rate device for interactive work.

Despite this limitation on high speed imaging, the development of the slow scan CCD camera in a form suitable for transmission electron microscopy has revolutionised electronic recording and will eventually displace the photographic plate. Not only does it have the capability to record single electron events but it also has a higher dynamic range and can acquire both the strong Bragg spots and the weak diffuse scattering in a single exposure. CCD chips with 1024 x 1024 pixels are now available and these should be more than sufficient for most applications. The limitations usually arise in attempts to display the results as photographic prints, though some idea of the quality of the data can be obtained by examining the high resolution image of Fig 2a and the diffraction pattern of Fig 2b.

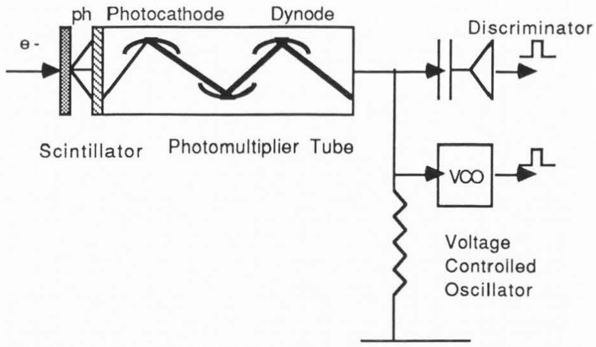


Figure 3 Schematic representation showing single electron counting and voltage-to-frequency analog recording using a scintillator photomultiplier combination.

Scanning Microscopy

The requirements for STEM are different both because the rate at which signals can be accepted varies over a wide range and because a number of different signals must be handled at the same time. It is convenient to divide STEM signals into those that can be acquired quickly which can be used for interactive real time manipulations such as specimen translation or focussing, and weak analytical signals that are acquired slowly. Examples of signals that can be used interactively are bright field, low angle dark field, secondary electrons and, for bulk specimens, backscattered electrons and specimen current. The list of weak analytical signals is endless but energy dispersive X-ray, energy loss, Auger and high angle dark field are among the most popular. All of the high rate signals and some of the analytical signals make use of an electron multiplier in the detection chain[2]. Frequently this consists of a scintillator to convert the incident electrons to photons and a photomultiplier to detect and amplify the photon signal. For secondary electrons an accelerating potential is applied so that enough photons are generated for each electron. In UHV systems direct electron multipliers such as channeltrons are common for detecting both Auger and secondary electrons. All electron multipliers can directly output a current that can be digitized using either a flash converter or the more accurate but slower successive approximation converter. Alternatively the pulses corresponding to the arrival of single electrons can be discriminated and converted to standard TTL pulses which are summed in a counter as shown schematically in Fig. 3. The image is formed by stepping the beam along a line while waiting for a fixed time at each

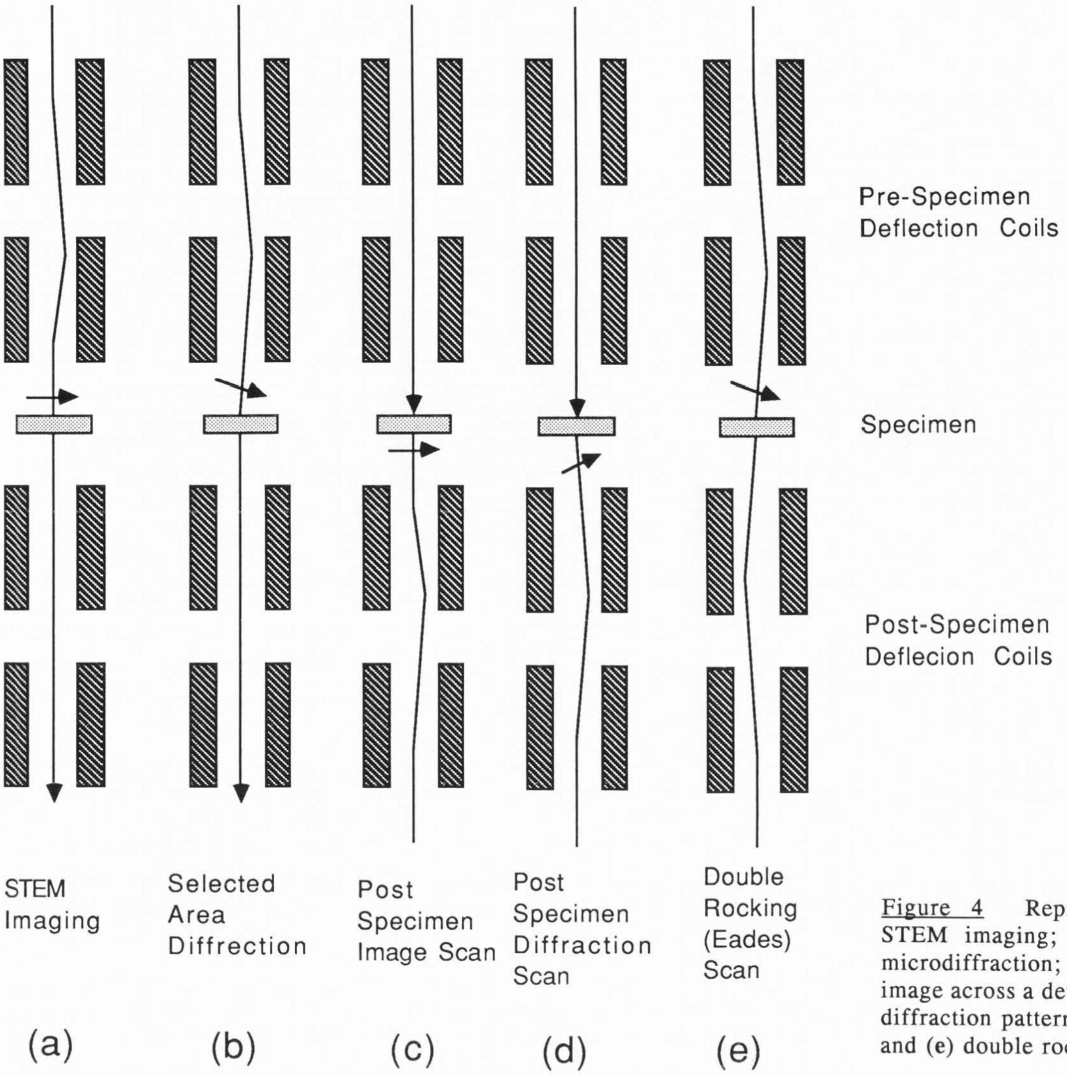
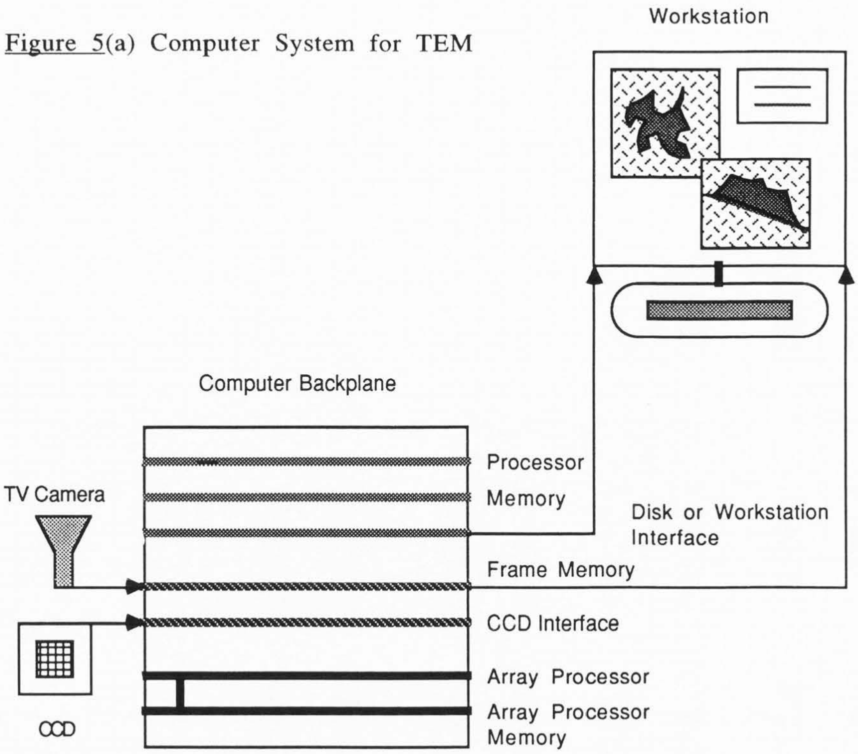


Figure 4 Representation of (**a**) STEM imaging; (**b**) rocking beam microdiffraction; (**c**) scanning TEM image across a detector; (d) scanning diffraction pattern across a detector; and (**e**) double rocking (Eades) scan.

point. Successive lines are scanned in sequence. Due to pulse pile up it is not possible to discriminate adequately when the input rate exceeds 10 Million/second and for many practical purposes 2 Million counts a second should be considered as the upper limit for single electron counting. This means that at the maximum count rate of 10MHz the minimum time per pixel needed to saturate an 8 bit frame buffer is 25μsecs. This minimum time is much longer than a basic "move" or "add" instruction on even a rudimentary personal computer, so for single pulse counted signals it is quite acceptable for the processor to directly control the scanning of the beam from one pixel to the next using digital to analog converters.

At higher signal levels a switchover should be made to analog to digital conversion. It is often convenient to use a voltage controlled oscillator to give pulses at a rate proportional to the signal (a voltage to frequency converter). This is also shown in the schematic diagram of Fig. 3. These pulses can then be counted by the same counter as used for single electron counting. As the limit of voltage to frequency converters is about 10MHz the same considerations on time per pixel apply. For strong signals, the frame times are limited by the maximum rate at which current through the scan coils can be changed without giving unacceptable distortion. This is controlled by the inductance of the scan coils and the liner tube. Although in some scanning instruments it is possible to scan at TV rates in many systems the maximum rate is about 8 to 10 frames/second. If the image has 512 by 512 pixels the input data rate is about 2 Million points per second. This is too fast for a computer processor to accept, and it is better to handle the data with a special board that acquires one line at a time and then sends the data by direct memory

Figure 5(a) Computer System for TEM



access (DMA) to the frame buffer. Any arithmetic operations involving the incoming data stream and the stored data will also have to be handled by this special board. Some early systems[1,6,16,33,32], had fast hardware driven scans, even if they sometimes lacked a frame buffer to store the data.

An advantage of digital imaging is that an image can be displayed at all times from the frame buffer independently of the speed at which the beam is scanned across the specimen. This is much more convenient than the traditional scanning microscope displays which were scanned in synchronism with the raster on the specimen. Even with long persistence phosphors it was difficult to work with weak signals where long integration times are necessary.

Although it is conventional to think of a scanning system only in terms of images the same hardware can also be used for various diffraction experiments. By altering the point about which the beam pivots using a double deflection coil set above the specimen[17] it is possible to obtain selected area diffraction by rocking the beam on the specimen and images with a parallel scan . Similarly using a double deflection set below the specimen (often called Grigson coils in a STEM) an image from parallel illumination or a diffraction pattern can be scanned across a point detector. By feeding the scan into both pre and post specimen coils the effect of specimen tilt can be simulated with a double rocking (Eades) scan[5]. These possibilities are all illustrated in Fig. 4.

Image Processing

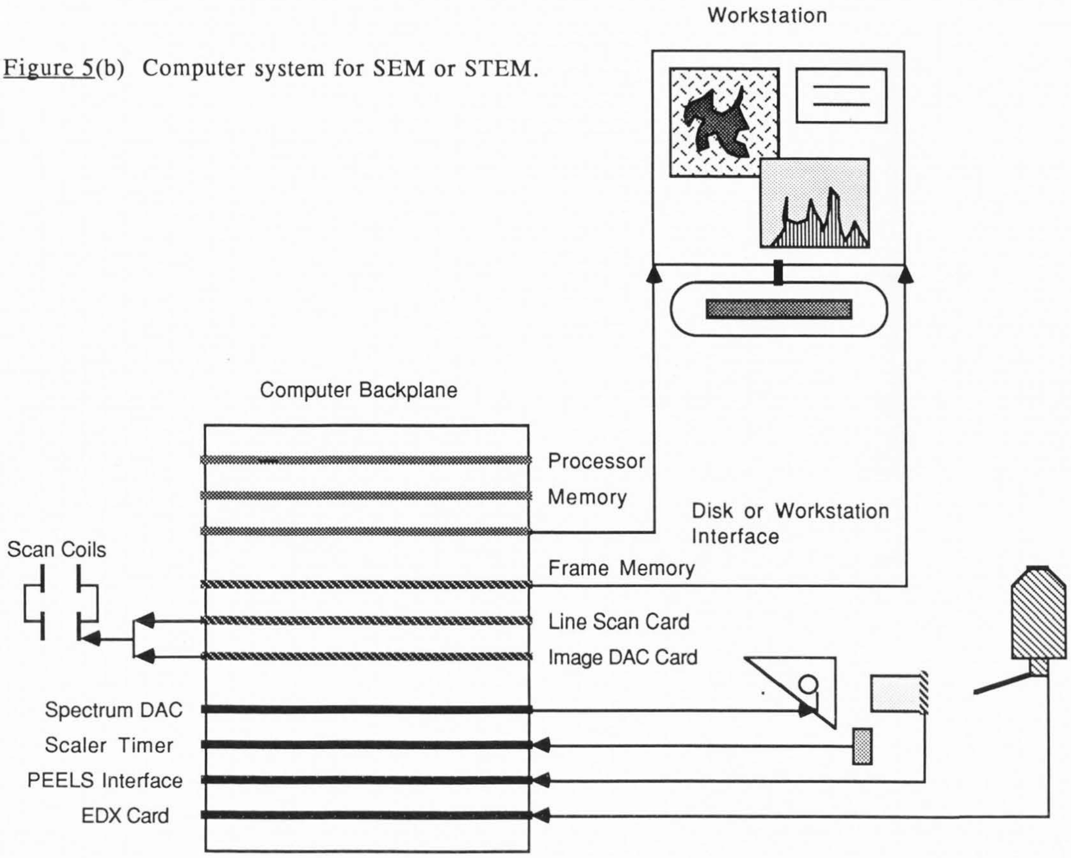
The strongest case for digital image acquisition is that various processing operations can be performed in a reliable manner online. The simplest operations involve changing the appearance of an image by altering contrast, brightness or colour using a look up table. Transformations using look up tables are instantaneous as the numerical value of the image point acts as the address into the look up table memory. The contents of this address are then displayed. Look up tables can also be used for logarithmic transformation and inversion.

Summing images to improve the signal to noise ratio is a relatively simple processing operation as it only involves manipulating the value of individual pixels[7,18,12,28]. Normally such operations are implemented directly in hardware in the general form

$$I_n = k_1 S + k_2 I_o \qquad (2)$$

where S is the incoming signal, I_n is the new content of the frame buffer, I_o is the old value in the frame buffer and k_1, k_2 are constants. The

Figure 5(b) Computer system for SEM or STEM.



advantage of hardware implementation is that the processing can be done at high speed, up to TV rates.

Other simple operations include those that involve a pixel and its neighbours. Examples are smoothing, differentiation and edge enhancement[26]. Mathematically they can be written as

$$I_{ij} = \sum_{m,n=-1}^{m,n=+1} K_{i-m,j-n} I_{m,n} \qquad (3)$$

where K_{mn} is a 3x3 matrix kernel and I_{ij} represents the image intensity. The same hardware that is used for signal averaging can also be used for these calculations with multiple passes through the arithmetic unit operating on shifted data from the frame buffer.

The real power of microscopy is its ability to give information in both real space and reciprocal (or scattering wave vector) space. Fourier transforms are, not surprisingly, frequently used especially in studies involving crystalline materials or microscope transfer functions. High speed Fourier transforms change the way the microscopist interacts with the instrument. Due to the dynamic range inherent in operations such as Fourier transformation it is better to perform them in floating point. A 512 x 512 complex Fourier transform takes about 5 seconds using a high speed RISC based workstation. An optimised array processor can perform the same operation in about 0.1 to 0.2 seconds which means that it is possible to update diffractograms in real time. The floating point array processor is an essential part of any image processing system and these days it is better to use it for all operations including simple manipulations such as signal averaging. There is much to be said for converting image data to floating point immediately, storing and manipulating it in floating point form and only reconverting the result to integer just before the final digital to analog conversion for display purposes. For a multiwindow display it would be converted to integer before the output image data is sent to the general display buffer (or before the signals from the general display buffer and the image display buffer are mixed). In fact many of the original image processing system designed for slow minicomputers (e.g. SEMPER[29]) were far ahead of their time as they worked entirely in floating point.

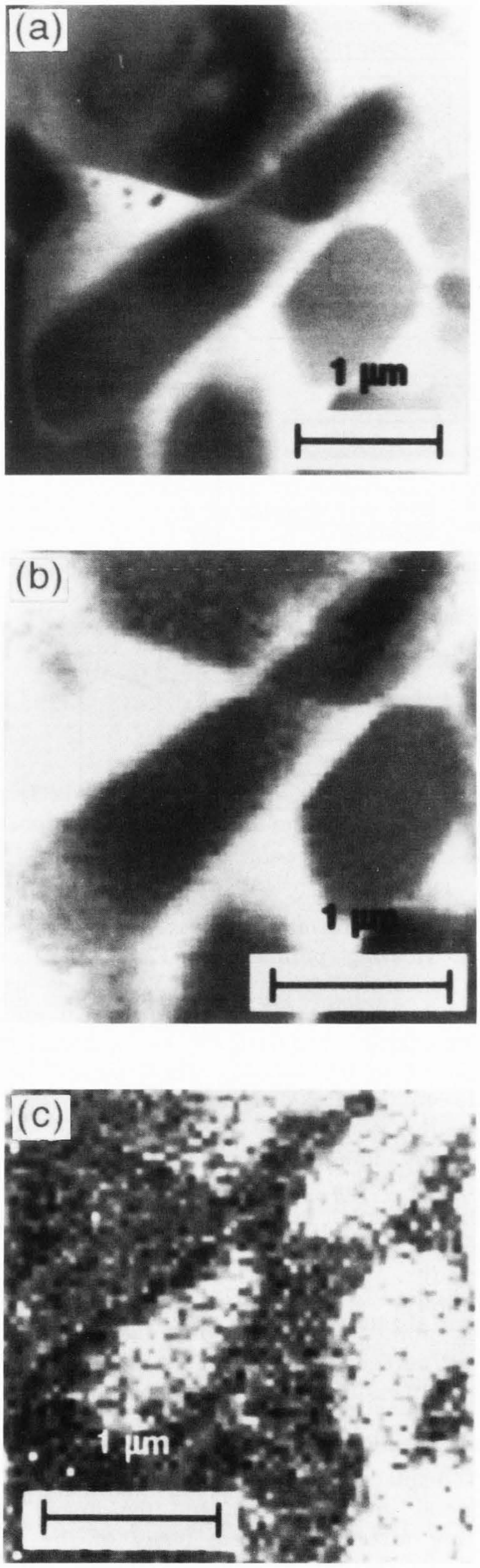


Figure 6 PEELS images of Si_3N_4/SiC ceramics (a) Bright field (b) N K edge (c) O K edge

System Design Considerations

A good way to build systems for microscopy is to use a standard computer bus as a foundation for specialised boards that cater to individual functions. A system for TEM could be designed as shown in Fig 5a. In addition to the usual components such as memory, processor and disk drives there should also be an image frame buffer, a board that accepts data from the CCD camera and an array processor[25]. There used to be a need for TV rate hardware for signal averaging but this is no longer necessary with the slow scan CCD camera where the integration time can be varied and the data rates are slow enough that arithmetic can be performed by the system processor.

A system for scanning and analytical microscopy would have some of the same components (see Fig. 5b). There might not be as much interest in online Fourier transforms so the array processor is not essential. In addition to a board that can perform fast line scans, as described previously, there will be specialised cards for different spectroscopies. Most serial spectroscopies such as serial energy loss, Auger or cathodoluminescene can be simply handled with a scalar timer in which counts are recorded for a preset time loaded into the counter[9]. As mentioned above the scanning of the spectrum or the image at a particular spectrometer setting can be performed by the processor since the data rates are so low that count times are 1 msec or longer. Many spectroscopy[8,10,15,27,31] and general computer based systems[22,23,24] for scanning microscopy have used processor driven scans.

Energy Dispersive X-ray spectroscopy gives pulses whose heights are proportional to the energies of the X-rays received by the detector. These are then digitized and act as the addresses to a set of memory locations. The contents of these addresses in memory are then incremented by one. Although the data rate are very low, usually 10kHz or less, and each pulse could be handled directly by the processor it is better to build the special memory on a separate board and have it accessed from the computer. Spectroscopies which use CCD or diode arrays (like PEELS) need hardware that can take the incoming data stream and send it directly to computer memory by Direct Memory Access[19], then signal the processor when the data has been transferred. Processing such as background subtraction might also be required at each point as in Auger or EELS. PEELS images with background subtraction and edge integration calculations performed at each pixel are shown in Fig 6b for the nitrogen K edge

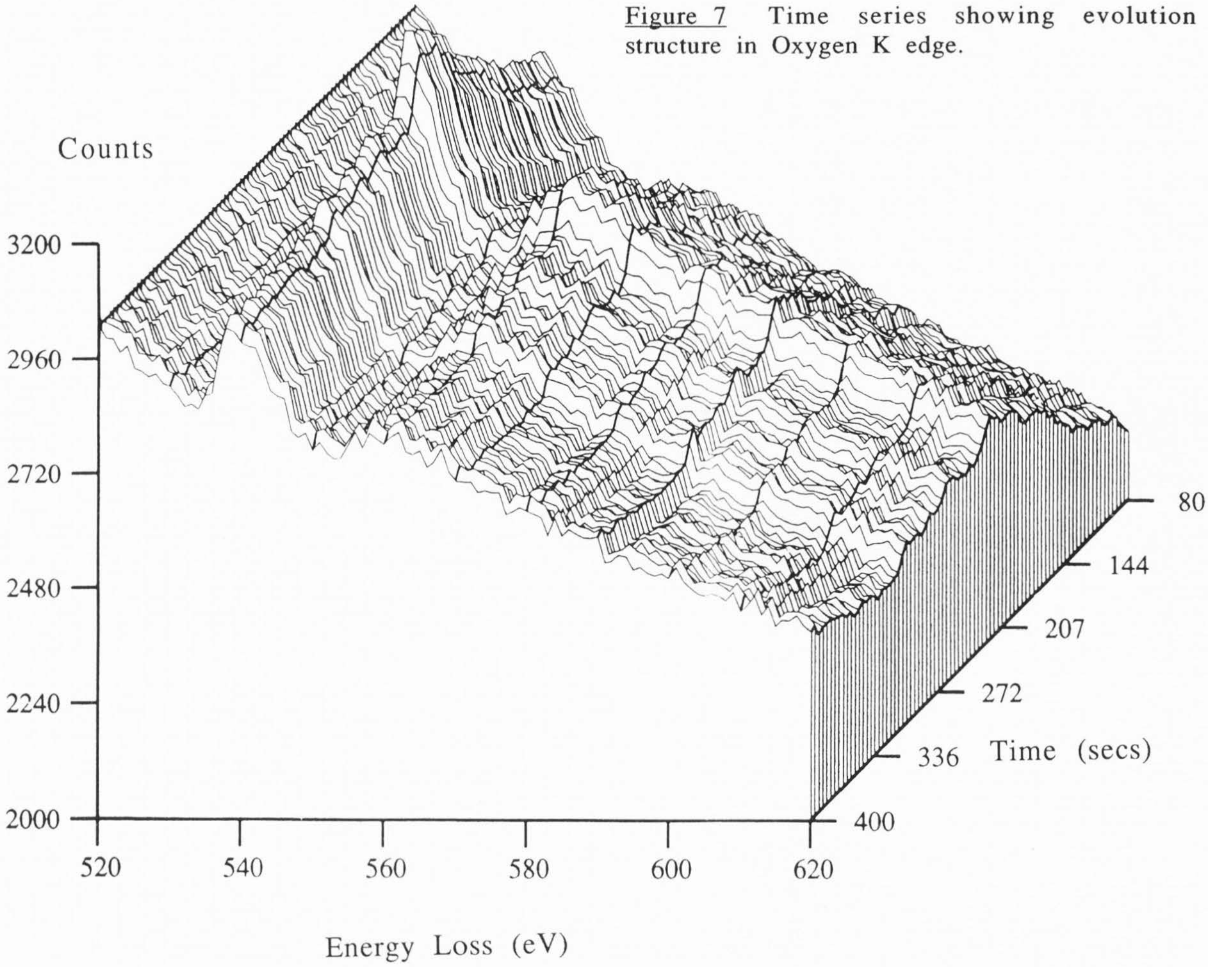


Figure 7 Time series showing evolution of structure in Oxygen K edge.

and Fig. 6c for the oxygen K edge in a Ceramic material. A comparison is made with the bright field image in Fig. 6a, acquired using a fast line scan card, as described above

All these specialised data acquisition activities at some time require that a signal be sent to the processor that interrupts the task that is running at that time. The processor then has to do whatever is necessary to handle the request for service. For PEELS or a CCD camera this might involve scaling the data for display; in the case of a fast scan card it would involve setting up the system for the next line of data. The process of changing from one task to another is called context switching, and during a context switch processor registers and common memory locations that are available to any task must be saved. In a system designed for multi-technique analytical microscopy, fast context switching is absolutely essential and the speed of a context switch is more important than the speed of the processor. Context switch time is very dependent on the nature of the operating system and simple real time single-user systems such as RT11 on the LSI 11 series or a PC under MSDOS provides much faster context switching times than UNIX or its variants running on a high speed workstation.

In analytical or scanning microscopy one would ideally want to switch between taking images interactively using bright field or secondary electrons (for example) and analysis of particular regions. A multi-window workstation display would be most convenient as images, line traces and spectra could all be displayed at the same time. The user could, with minimal difficulty, move a cursor to a new point, then take a spectrum or mark a region in the spectrum and use this in forming an image. The main problem with such systems is that access to the display memory is controlled by the windowing software and special graphics processors which mean that it is impossible to get direct fast access. This makes such systems of limited use for microcopy acquisition where the ability to view images and spectra as they are being acquired is of paramount importance. Of course there are various ways around these problems such as using an extra display memory for real time access and multiplexing the output with the workstation display. The slow context switching times also limit the ability of the system to perform adequately when dealing with multiple asynchronous analytical signals. Finally, most of the low cost workstations do not allow access to internal high speed buses and only allow connection to the outside world through a SCSI interface (Small Computer Systems Interface). The bandwith of a few Mbytes a second is adequate for disk drives but would be considered limiting for high data rate images. A possible solution for the systems designer is to build the acquisition and real-time display functions in a separate box based on a high speed bus such as VME and controlled by a processor running a stripped-down real-time operating system. The workstation would then become a sophisticated user interface with processing capabilities. This is, in effect, the route that most of the EDX manufacturers have chosen.

Although most analytical microscopists switch between spectra and images interactively it is sometimes valuable to be able to collect the complete spectrum at each image point (the spectrum image)[14,13]. When using parallel energy loss or energy dispersive X-ray the only penalty is the extra data transfer time and the storage requirements. A 256 x 256 point image with a 1024 point spectrum acquired at each point uses 64Mbytes of storage. This means that each spectrum or line of the spectrum image will have to be sent to the hard disk, as large amounts of memory are not usually available. At the slow data rates common in EDX this probably will not result in any delay, but for acquisition using PEELS the disk access and storage times will be greater than the acquisition time. The local hard disk will rapidly become full and it will be necessary to archive these large data sets on optical disks with gigabytes of storage. The advantage of the spectrum imaging is that all the data is available for later review and sometimes interesting features are discovered (such as the presence of an unexpected element) which were not noticed in the original session on the microscope. The disadvantage is the slowing down of the acquisition by the lengthy transfers of the spectra to disk.

At ASU we have found that a system which can quickly store a complete spectrum for a series of points along a line or a sequence of times is invaluable in many experiments. The data is stored instantly in computer memory that is normally inaccessible to the operating system and is retrieved at the end of the experiment to be stored on disk. This capability is very useful for studying radiation damage by monitoring composition and EELS fine structure changes with time. An example of a time series showing fine structure changes in the Oxygen K edge is given as Fig. 7. It has also been necessary in the microchemical analysis of thin oxide films which are hard to locate in the image as they have low contrast. These films also damage easily if a beam were to remain on them for too long. In this case the spectra are acquired as the beam is scanned across the film and the relevant spectra are extracted for later analysis.

Conclusions

We are now at the point where single electron counting in both scanning and transmission microscopy is a reality. In transmission microscopy the slow scan CCD camera not only gives better quality data but also simplifies system design. The main problems are that general purpose small computers and workstations are not ideal for optimised high data rate spectrum and image collection and display. On the other hand specially constructed systems lack the multiwindow friendly interfaces that have become prevalent on personal computers and workstations. The challenge remains to design systems that are friendly to the user, simple to modify for new detectors or experiments and at the same time have the computational and data transfer performance that is necessary for real time imaging. Although only hardware issues have been addressed in this paper the real power of any system comes from the software both in the form of the operating system and any special software developed for acquisition, user interface and analysis. Most of the effort in the construction of a system goes into the software development, the hardware only defines the physical limitations that will be imposed.

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Discussion with Reviewers

O.L. Krivanek: Since a 10MHz voltage-to-frequency converter (VFC) takes 26msec to count up to 256, attaining just 8 bit dynamic range with this device means acquiring images at less than 1/200th of TV rate. This is far too slow for any dynamic, on-line adjustments. What do the authors think of other conversion schemes such as the gated integrator or the integrating digitizer

(A/D conversions are performed at a constant fast rate and the results summed while the beam remains on one pixel) ?

Authors: There has always been a range of data acquisition speeds that has not been handled by either the fixed-rate 10MHz flash converters or the faster 0.5-1MHz successive approximation analog-digital converters. An integrating digitizer built from a flash converter and summing the results using standard TTL logic would nicely fill this gap

O.L. Krivanek: DMA of 16 bit words into the video memory or the main memory at 2 MHz is typically no problem on recent personal computers, and simple image processing operations can typically also be carried out at this rate. Furthermore, DMA of an 8-bit signal to a resizable window on the computer's main display at TV rate is also possible. Personal computers of the next generation are likely to have enough processing power for image compression/decompression at full TV rate (the stated aim is to be able to read/write TV-rate video images to/from a hard disk). Would the author's agree that the days of the separate frame buffer, which adds extra cost, restricts the flexibility of the processing, and limits the memory available for images are nearly over for anything other than imaging *plus* image processing at full TV rate?

Authors: We think that your views on the capabilities of personal computers (both present and projected) are somewhat optimistic. The TV rate displays in a resizable window are achieved by sending the data to a special memory which can also act as the display memory for the personal computer (see discussion in text). It is a matter of semantics whether you want to call this memory a frame buffer. We doubt that a personal computer can simultaneously DMA 16 bit data at 2 MHz and *process* it at this rate without some extra processing power. Whether the next generation of personal computers will have the power to perform *general* purpose image processing at TV rates will depend on market forces. If there is a requirement for compression/decompression it would be better to use an application specific chip that implemented a particular algorithm. This might be of no use in electron microscopy. At the same time we see that the separate frame buffer is likely to disappear because the data input rates from CCD cameras and scanning microscopy are much lower than TV rates. A perfectly adequate system can be devised using the computer's main memory and display buffer.

P. Atkin: Is a 3x3 convolution operation useful? For what? Is it worth implementing in hardware as a special case?

Authors: We believe a 3x3 convolution is useful because it represents a "standard" in image processing and enables microscopists to make contact with a wider community of scientists using digital image processing. At the same time our experience shows that 3x3 convolutions have not been widely adopted by microscopists. We think that they should be implemented in hardware only if there is a need to perform the operations in real-time.

P. Atkin: What do you mean by "real time"? What is a "real time" diffractogram, for example? At what speed is a diffractogram calculation "fast enough"?

Authors: For us "real-time" means that the display is updated frequently enough for the operator to perform some interactive manipulation (such as specimen translation or focussing or alignment) without wishing to kick the machine in frustration. In practice this means that 16 updates/second would be nice for a near perfect display and 4 updates/second is barely acceptable. Since alignment using diffractograms is so convenient compared to staring at the granularity of amorphous images we believe users will tolerate a lower update rate of maybe 1 to 2 diffractograms/second.

P. Atkin: For EDX why not handle each pulse directly with the main processor rather than use the special hardware described in the text?

Authors: There are two reasons for using specialised hardware to handle EDX pulses. The first problem is that even though the average rate of arrival of EDX pulses is quite low, it is still possible for two pulses to arrive in the time taken by the interrupt service process. The second reason is that interrupt latencies can be long and unpredictable (up to 50-100μsecs) and the context switching times even longer (depending on operating system). It is bad enough loosing data due to the pulse shaping requirements, there is no need for the digital hardware to impose further limitations. It is quite acceptable to build the specialised hardware around a dedicated microprocessor (ORTEC use a Z80 in their ADCAM unit) with a dual ported memory that communicates with the main processor as and when necessary.

P. Atkin: What are the relative merits and demerits of say, MS-DOS and UNIX when used to control real time image processing systems of the type you describe? For example, how can one cope with the *potentially unlimited* response time of UNIX?

Authors: Any single-user operating system such as MS-DOS has advantages over an operating system such as UNIX because an interrupt can directly communicate with a program under a single-user system. To the best of our knowledge, the only way to achieve real-time response in a "standard" UNIX is to change the Kernel by directly inserting real-time processes. (see M.J. Ibach, "The Design of the UNIX Operating System" Englewood Cliffs, Prentice Hall) 1986, p 258). The main problem is that the scheduler preempts all processes in making decisions about use of the processor. Another problem with UNIX for image processing is the clumsy file handling system which fragments large files all over a disk.

P. Atkin: Almost all new array processors are now built using the same technology which makes up modern workstations (ie RISC processors with integrated floating point such as the Intel i860 and the MIPS F4000). Why do your benchmark timings show such a difference between a workstation and an "optimised array processor"? Could it be that the primary difference is *software*, rather than the hardware?

Authors: The dividing line between *software* and *hardware* can be a very thin one. The performance of a system using a given processor chip is often decided by the type of memory and its organisation The programming of the chip, often implemented in ROM, is also crucial. Whether programs in ROM are best described as "software", "hardware" or "firmware" is a semantic point. It is not surprising that the performance of the same chip, when used in different applications, can be very different.

P. Atkin: I find your views on the desirability of floating-point rather simplistic. Would you agree with my assertion that if the calculation does not require the dynamic range of a floating-point representation, then to implement a process in fixed point at a given speed is cheaper, uses less memory, less bandwith, less board area and less power? If so, can you indicate the design considerations which should be taken into account when making the choice between integer and floating-point representations?

Authors: We agree that a fixed point implementation costs less, uses less power, less bandwith and sometimes less board area. At the same time we have found that the practical advantages of working in floating point outweigh the small savings made using a fixed point implementation. This is especially true in a system used in development of new algorithms or techniques of image processing. Programmer time is the most expensive resource in any system development and much time can be saved when one does not have to worry about the frequent overflows that occur with fixed point integers. In the end it is a matter for individual judgement but we believe that it is worth spending an extra few hundred dollars on hardware in a system that might cost the user fifty thousand dollars.

R.H. Tietz: To what extent has computer software been developed to enable fast and efficient administration and processing of the vast quantities of data resulting from the new line-mapped, image mapped and time mapped spectral data which can now be acquired?

Authors: We don't believe much thought has been given to software for administration and processing of large "spectrum-image" data sets. Specialised routines for processing have been developed at ASU and by John Hunt[13] at Lehigh. There are also programs for multivariate statistical analysis (see the article by N. Bonnet in these proceedings). At the present time there are no general-purpose "user-friendly" packages that can be implemented on a wide range of different systems. Furthermore we believe that the file handling in the ubiquitous UNIX operating system, which is standard on nearly all work stations, will cause further problems, with much unnecessary degradation in performance. In the UNIX environment it will probably be better to treat the "spectrum-image" as a "tape".

R.H. Tietz: What are the limitations of present electronics for image acquisition and could you give an indication of future trends in this field?

Authors: We see three main limitations at the present time. There is a limitation of a few MHz in the rate that single electron signals can be detected and discriminated. This is probably not very serious, as at these rates single electron counting does not give a significant improvement in signal to noise ratio. The second limitation relates to the speed with which images can be captured. It would be nice to be able to capture images (albeit at low pixel resolution) at rates of up to 100 frames/second for dynamic experiments. We would still like to replace the TV camera and video recorder with a digital system that is not limited by distortions and low dynamic range. The third problem is the lack of data management software for the gigabytes of digital images that will be produced in the coming years.