The Development of a High-Speed 100 fps CCD Camera*

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Abstract #30

This paper describes the development of a high-speed CCD digital camera system. The system has been designed to use CCDs from various manufacturers with minimal modifications. The first camera built on this design utilizes a Thomson 512x512 pixel CCD as its sensor which is read out from two parallel outputs at a speed of 15 MHz/pixel/output. The data undergoes correlated double sampling after which, they are digitized into 12 bits. The throughput of the system translates into 60 MB/second which is either stored directly in a PC or transferred to a custom designed VXI module. The PC data acquisition version of the camera can collect sustained data in real time that is limited to the memory installed in the PC. The VXI version of the camera, also controlled by a PC, stores 512 MB of real-time data before it must be read out to the PC disk storage. The uncooled CCD can be used either with lenses for visible light imaging or with a phosphor screen for x-ray imaging. This camera has been tested with a phosphor screen coupled to a fiber-optic face plate for high-resolution, high-speed x-ray imaging. The camera is controlled through a custom event-driven user-friendly Windows package. The pixel clock speed can be changed from 1 MHz to 15 MHz. The noise was measure to be 1.05 bits at a 13.3 MHz pixel clock. This paper will describe the electronics, software, and characterizations that have been performed using both visible and x-ray photons.

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Introduction

The advent of insertion device based high-brilliance synchrotron sources have exposed the field of x-ray scattering to new techniques[1-3], and has also taken established techniques to new levels of sophistication. For example, in the high-speed regime of the field of time-resolved x-ray scattering, it is now possible to perform picosecond Laue scattering[4] on extremely small samples. There are no x-ray detectors available today that fully exploit the characteristics of third generation synchrotron sources. Large area detectors capable of KHz framing rates are under development[5-7]. In the interim for time-resolved x-ray scattering, charge coupled device (CCD) detectors with multiple outputs are the best choice for high-speed, reasonable size applications. CCDs are excellent detectors of visible light and to some extend, can detect x-rays. Unfortunately, their serial readout, where each pixel is clocked out individually, limits the maximum speed at which they can be clocked. One solution is to increase the number of output ports. Currently, commercial scientific grade CCDs are available with 2 to 32 output ports having pixel formats from 512x512 to 2048x2048 with framing rates up to the KHz range.

Although CCDs capable of high framing rates are available, the electronics required to drive them, digitize the data and store it can be challenging. For a CCD with 16 outputs being clocked in parallel after 12-bit digitization, the throughput of the system is 480 MB/second; far more than what any commercial data acquisition system can sustain. Hence, for sustained data acquisition, one has to develop a custom data acquisition system to store the data from such a device. During an experiment, the data is stored in real time in the custom data acquisition system after which, it is transferred at a much slower rate to disk arrays for analysis. The system must be expandable to account for devices with more outputs.

Perceiving that multiple output CCDs, with more than 32 outputs, are going to become available in the near future, and also to satisfy our own hybrid pixel array detector (PAD) development project[5], we have developed a prototype set of electronics to satisfy the requirements for a 512x512 CCD with 2 outputs that is clocked at 15 MHz/output. The same system is also used to control a 1024x1024 pixel CCD from Texas Instruments that is read-out as a 512x512 device through one of its two outputs. The design of all the electronics and software to control it is easily expandable to account for CCDs and related detectors with more than two outputs. The system is being used presently to design the electronics for a 4 output 1024x1024 CCD, a 16 output 512x512 CCD and a multiple output PAD. This paper describes the mechanical design of the camera, operation, data acquisition and control along with the graphical user interface, and characterization

Mechanical Description and Operation

To minimize noise, the camera is designed with all electronics to control the CCD in a custom 3U chassis that resides on the camera head itself. The backplane forms the backbone of the camera on to which, on one side, is the CCD board, and on the other side reside the boards to control the CCD. All boards except the backplane and CCD board are standard 3U size; namely 10cm x 16cm. The interconnects between boards are through a 96 pin DIN connector (3x32). On these connectors, row B is ground while the signals are on rows A and C. The multilayer backplane has rows A and C interconnects sandwiched between ground planes. The chassis houses multilayer printed circuit boards for the voltage regulators, pulse pattern generator (PPG) and drive electronics, correlated double sampling 12-bit analog to digital converter and digital interface, backplane board, and CCD board with signal conditioning and amplification.

Figure 1 is a block diagram of the operation of the camera. Functionally, the hardware has three components 1) Drive board, 2) Sensor board, and 3) ADC board. Readout is initiated by either software or by a shutter after the sensor is exposed to light (or x-rays). The shutter (or software) sends a signal to the drive board that resets the PPG circuitry which causes it to send the waveforms needs to readout the CCD to the MOSFET drivers. The sequence consists of a row readout sequence of serial and parallel readout waveforms. This pattern is repeated to readout all the rows of data. The PPG also send the video hold, reference hold, pixel clock, line enable, and frame enable signals t the ADC board. The PPG is programmable to allow for flexible modes of readout for higher speed applications[8]. Between the MOSFETs and CCD are small series resistors to attenuate reflections that might occur. The analog output of the CCD is then AC coupled and buffered before it reaches the ADC board. The signal is buffered using a high bandwidth, low-offset operational amplifier.

Although data is digitized to 12-bits and the CCD has two outputs for a maximum throughput of 60 MB/second, the bandwidth necessary for the data is 80 MB/second just because most computer memory, peripheral equipment and software is defined on the byte boundary. Hence for this camera the data throughput, of 80 MB/second, is not sustainable by standard computer disk systems. To overcome this problem, two approaches were taken. One, for a limited number of frames (in the range of ten to hundred), an Imaging Technology, Inc. IC-PCI Digital Camera Interface 24-bit digital input card that resides in the PCI slot of a Pentium PC is used for data acquisition. And the other approach, for a thousand frames of sustained data, a VXI based two channel memory module with 512 MB of DRAM was designed.

The PC platform consists of a Micron Millennia Pentium P5-133 PC with a Micronics Triton motherboard, 128 MB RAM, 4 GB SCSI hard disk, IC-PCI Digital Camera Interface, and a Diamond Stealth64 (S3-968) 4 MB VRAM video card. The IC-PCI card is capable of capturing 24-bit (3 bytes) data at the rate of 120 MB/second (40 MHz). The maximum output rate of each 12-bit ADC is 20 MHz. The system is connected such that the two 12-bit words are combined into a 24-bit word that is then captured by the IC-PCI card and block transferred to the PC's main memory, and eventually stored on the hard disk.

For CCDs with more than two outputs and for experiments where the data sets need to be more than a hundred, the VXI memory module was designed and developed. The memory card has two input channels, each capable of capturing data at 40 MB/second. The card an be configured with each channel having 256 MB of storage or chaining the two channels (by software) such that one input is 512 MB deep. The data is then readout (at a much slower rate of 4 MB/second) to the host PC over the VXI backplane. The PC is connected to the VXI crate using National Instruments MXI-II bus.

The software for the CCD camera is a Microsoft Windows program running under Windows 95 with a PCI bus. The software uses an IC-PCI card from Imaging Technology, Inc. or uses the VXI memory system to capture and process the images. Features of the software include real-time capture, live display of images at different gray scale or color levels, saving images to disk, and some basic image processing functions like mean and sigma measurements over a selected area, histogramming, and row and column profiling. In addition, the software is designed to be user friendly and supports the standard Windows help function.

Detector Characterization

Using visible light, the photon transfer technique[9,10] has been utilized to yield detector characterizations of linearity, dark current, electronic read noise, full well saturation levels, signal to noise ratio, dynamic range, and electrons/analog-to-digital unit. All of these parameters are obtained from one procedure, in which images are captured at a series of integration times with a uniform light source. The resolving power in the form of a Modulation Transfer Function (MTF) has been characterized using the knife edge technique[11].

The primary characterization performed on the camera was a test for linearity, which also provides data applicable to a number of other characterization attributes. The test for linearity was performed by capturing a series of images of a uniformly illuminated field at varying integration times. A high intensity LED, diffused with an 8" diameter integrating sphere and ground glass, was used as the light source. With the voltage to the light source held constant, integration times were bracketed from 1 to 250 milliseconds with a waveform generator that triggered the readout of the camera. The waveform generator also extinguished the LED during the CCD read time, thus acting as shutter to prevent extraneous exposure during readout.

For each integration time, two image frames were captured along with two dark frames. For the linearity characterization, data points are generated by subtracting one dark frame from one image frame (to remove offset dark current) and calculating the mean over a 20 x 20 pixel region at the center of each of the two image outputs. Although each output of the CCD leads to identically configured circuitry, there is a potential for small variations between the two channels due to component tolerances. Figure 2 shows the linearity of the camera for each output channel. The results indicate that the camera's response to radiation is linear to within 3% over the entire, 12-bit dynamic range.

The photon transfer curve is a plot of random noise as a function of the signal (adu). The signal noise is defined as the square root of the variance of the signal, with the fixed pattern noise removed. Fixed pattern noise is removed by subtracting two images taken back to back at the same exposure level. The variance is computed over a region of the differenced image and divided by two (because the rms noise increases by the square root of 2 when two identical frames are either added or subtracted).

According to Poisson statistics, the noise is proportional to the square root of the signal when outside the single photon counting regime. It follows, that the photon transfer curve plotted on a log-log plot should yield a slope of 1/2. Because the photon transfer curve includes both the read noise and the shot noise, the curve is nonlinear at low signals where the dark current noise has a considerable contribution, and becomes linear as the shot noise of the signal overpowers the read noise. Figure 3 is the photon transfer curve, showing the anticipated slope of 0.5 for the straight line portion of the curve to within +/- 15%.

Because the camera is maintained at room temperature, the read noise is expected to rise with increasing integration time due to thermal effects. Dark current noise is calculated as square root of 1/2 the variance of two differenced dark images, as described above. The dark current RMS noise remains below 1.6 for integration times up to 250 milliseconds with noise values as low as 1.05 for the shortest integration times.

The calculated dynamic range is 3900 (4095/1.05), meaning that the camera can resolve intensity changes as small as one part in 3900.

Assuming negligible read noise, and a quantum yield of 1, the signal to noise ratio is:

$$S/N = S/(S)^{1/2} = S^{1/2}$$

S/N is often given in decibels, where the conversion is defined as:

$$dB = 20 \log (S/N)$$

When calculating signal to noise ratios, the signal must be in terms of electrons, because the S/N changes depending on the energy of the radiation. The gain constant, K, is used to convert adu to units of electrons. We will use the average value of constant K (electrons per adu), 80 e^-/adu as obtained from the photon transfer curve.

$$S/N = (4095 \text{ adu} * 80 \text{ e}^-/\text{adu})1/2 = 572 = 55 \text{ dB}$$

Using actual measured data points for maximum signal and noise:

$$S/N = (3835\ \text{adu} * 80\ e^-/\text{adu}) / (7.68\ \text{adu} * 80\ e^-/\text{adu}) = 499 = 54\ \text{dB}$$

The measured S/N varies from the ideal calculation by less than 2%.

The MTF is generated from imaging a knife edge onto the detector. A profile of the edge is called the edge trace function, e(x). The first derivative of the edge trace function gives the line spread function, L(x). The Optical Transfer Function (OTF) is the Fourier transform of the line spread function, and the MTF is defined as the absolute value of the OTF. MTF was measured using visible light and 8 KeV x-rays. For the x-ray measurements, a 60 μm thick GdOS:Tb phosphor was bonded to the fiber-optic face plate of the CCD.

A high intensity LED was used as a light source for the visible MTF measurements. The beam was collimated using a pinhole and a lens positioned one focal length from the pinhole. One image was used to generate multiple edge trace functions. The MTF was calculated independently for 80 rows and averaged. Because the knife edge was intentionally placed at a slight angle with respect to the fixed pixel grid, the averaging served to increase effective sampling across the edge and to reduce noise. The detector, with a 1:1 fiber optic face plate, is capable of resolving 12 line pairs per mm at 50% contrast. This resolution corresponds to the width of 4.4 pixels (1/12 line pairs per mm = 83 microns per cycle; 83 microns/19 microns per pixel = 4.4 pixels) such that one cycle, (light to dark to light fluctuation) spanning 4.4 pixels would be imaged to 50% its physical contrast. The x-ray measurements for the MTF were performed using synchrotron radiation x-rays at the Advanced Photon Source. The resolution obtained at full width half maximum level with x-rays corresponded to about 100 microns/line. Figure 4 shows the MTF for visible light and x-rays along with an ideal MTF generated from a digitally created, one-bit, edge.

Conclusions

Using the mechanical and electrical framework of this camera, 4- and 16-output high-frame rate cameras are under development. The present camera system is also capable of being operated in a streak readout mode with a time resolution of 60 μseconds for one-dimensional images. The characterization data shows that the present camera system has met the design goals of 12-bit dynamic range, high frame rate, X-ray sensitive, and it is packaged in a relatively portable system.

Figure Captions

Figure 1. Schematic diagram of the operation of the CCD camera

Figure 2. Linearity measurements using visible light for each output channel.

Figure 3. The Photon Transfer Curve for both outputs channels. The straight dashed line is an extrapolation of the straight portion of the curve. The camera gain constant, K, is approximated by the signal intercept of this line.

Figure 4. Modulation Transfer Function (MTF). Solid line is actual MTF with visible light, dashed line with x-rays, and dotted line is ideal MTF.

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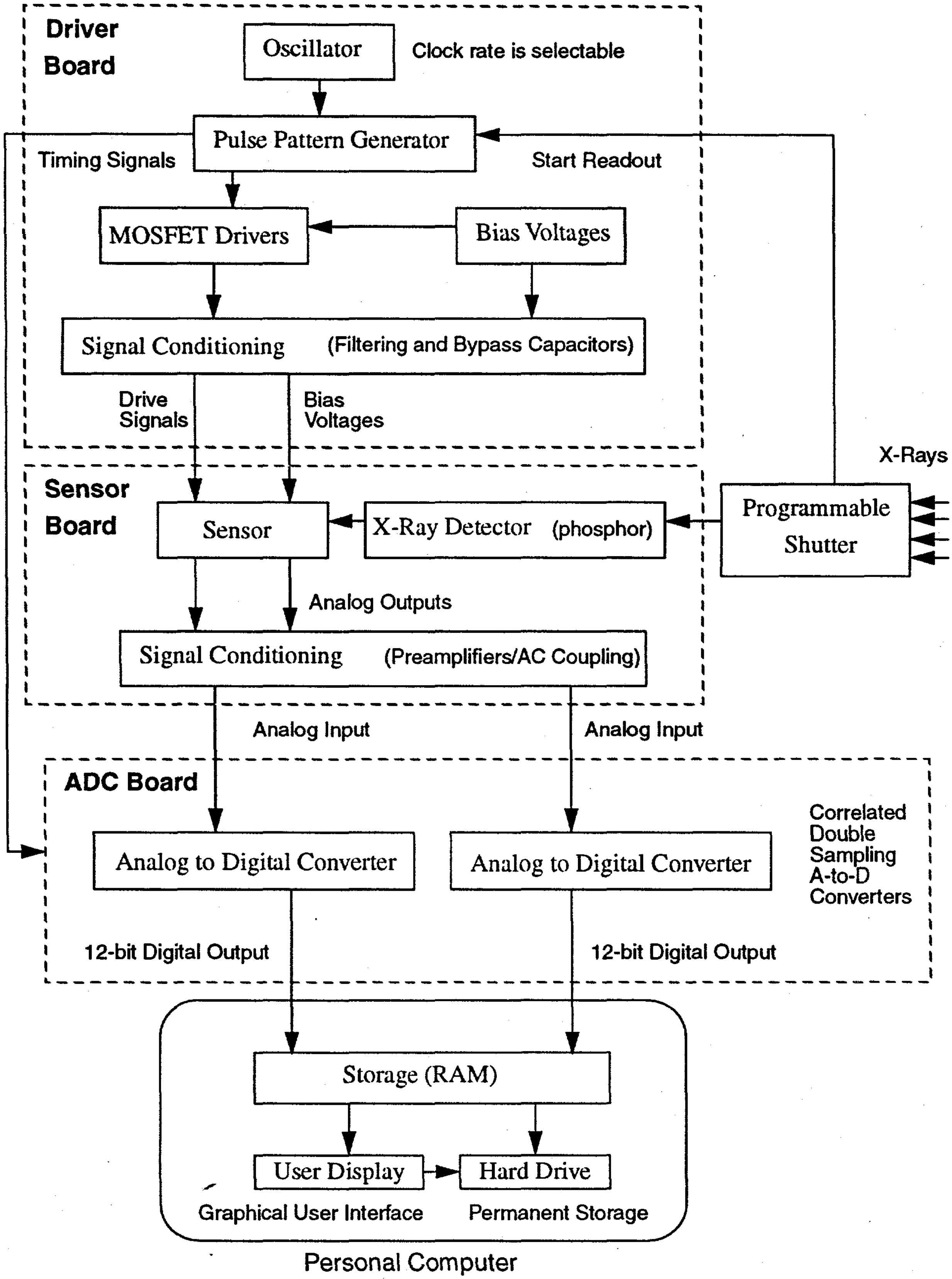
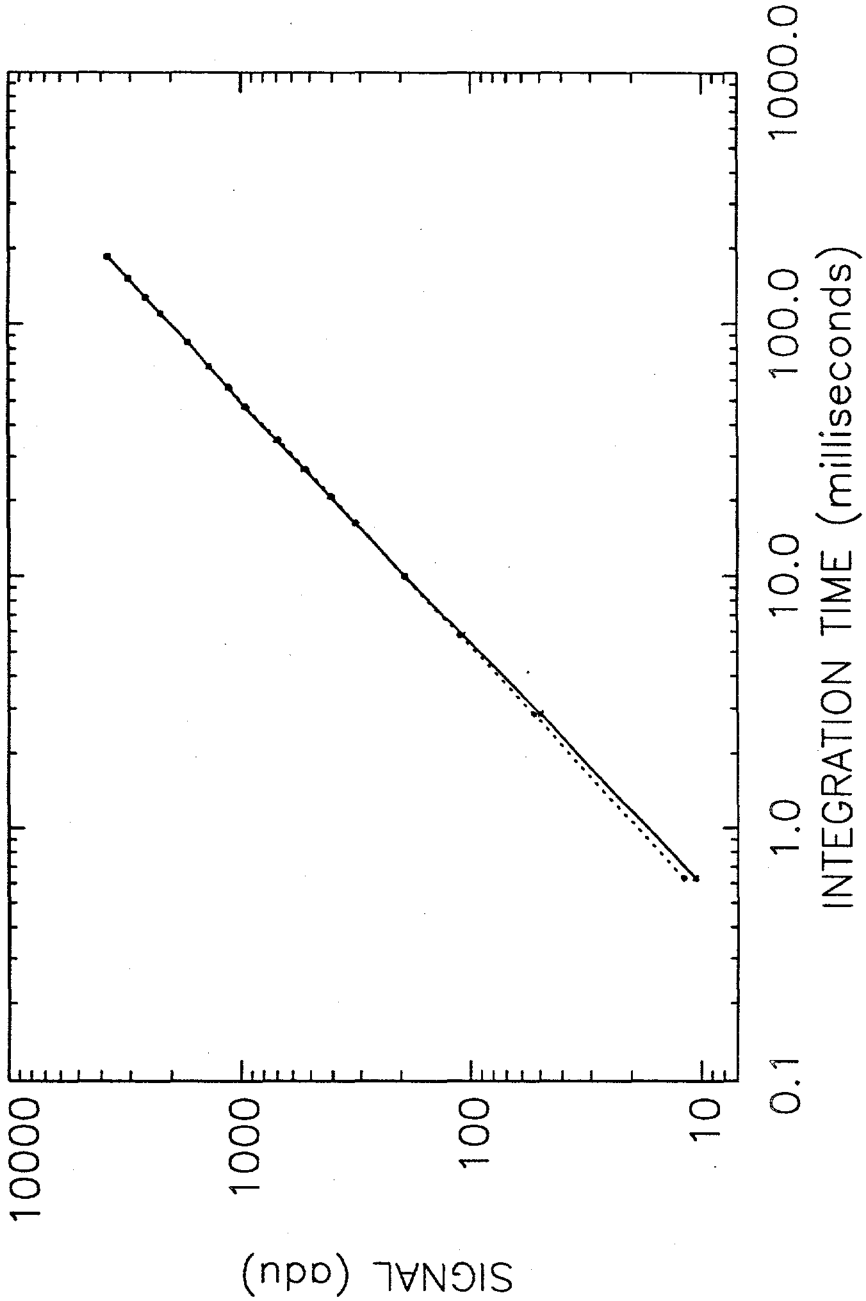
Figure 1



Driver Board
Oscillator
Clock rate is selectable
Pulse Pattern Generator
Timing Signals
Start Readout
MOSFET Drivers
Bias Voltages
Signal Conditioning (Filtering and Bypass Capacitors)
Drive Signals
Bias Voltages
X-Rays
Sensor Board
Sensor
X-Ray Detector (phosphor)
Programmable Shutter
Analog Outputs
Signal Conditioning (Preamplifiers/AC Coupling)
Analog Input
Analog Input
ADC Board
Analog to Digital Converter
Analog to Digital Converter
Correlated Double Sampling A-to-D Converters
12-bit Digital Output
12-bit Digital Output
Storage (RAM)
User Display
Hard Drive
Graphical User Interface
Permanent Storage
Personal Computer

Figure 2



SIGNAL (adu)
10000
1000
100
10
0.1
1.0
10.0
100.0
1000.0
INTEGRATION TIME (milliseconds)

Figure 3

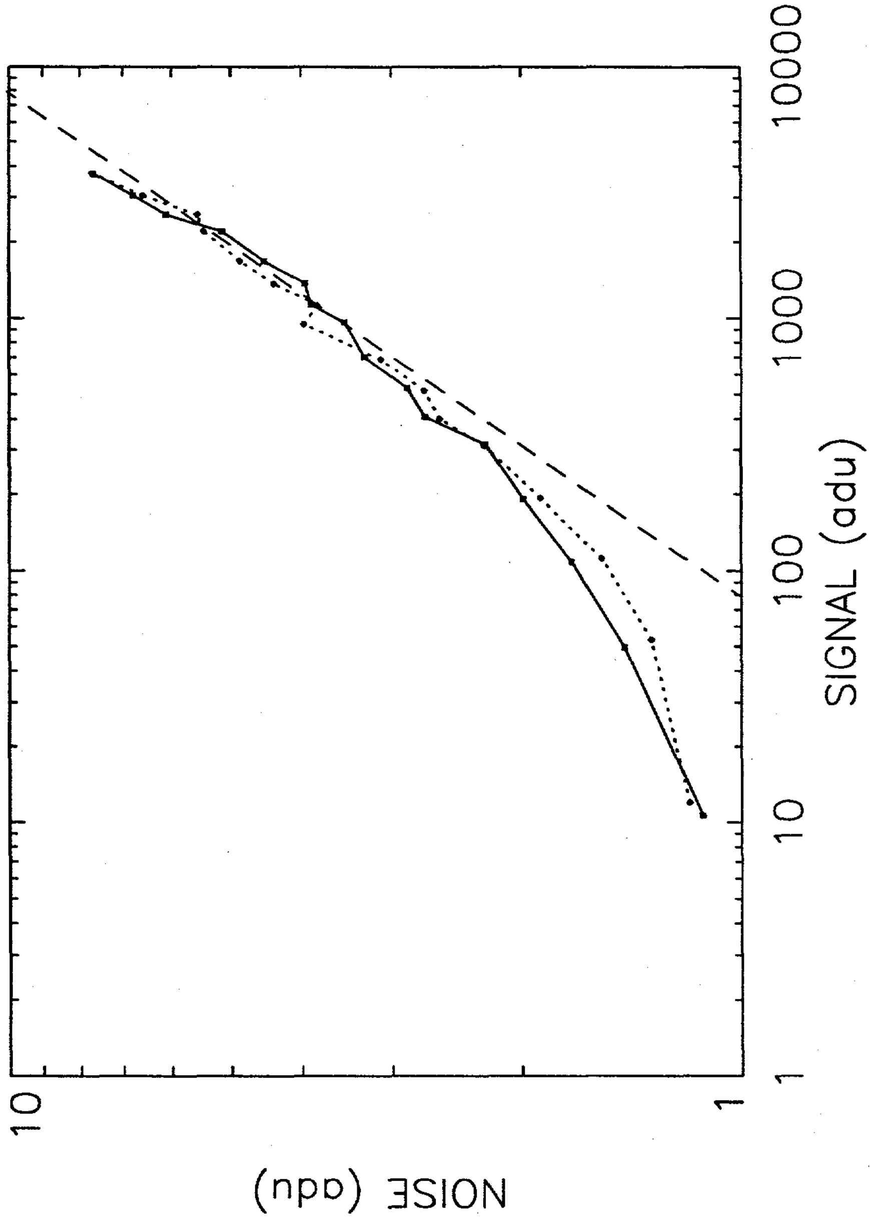
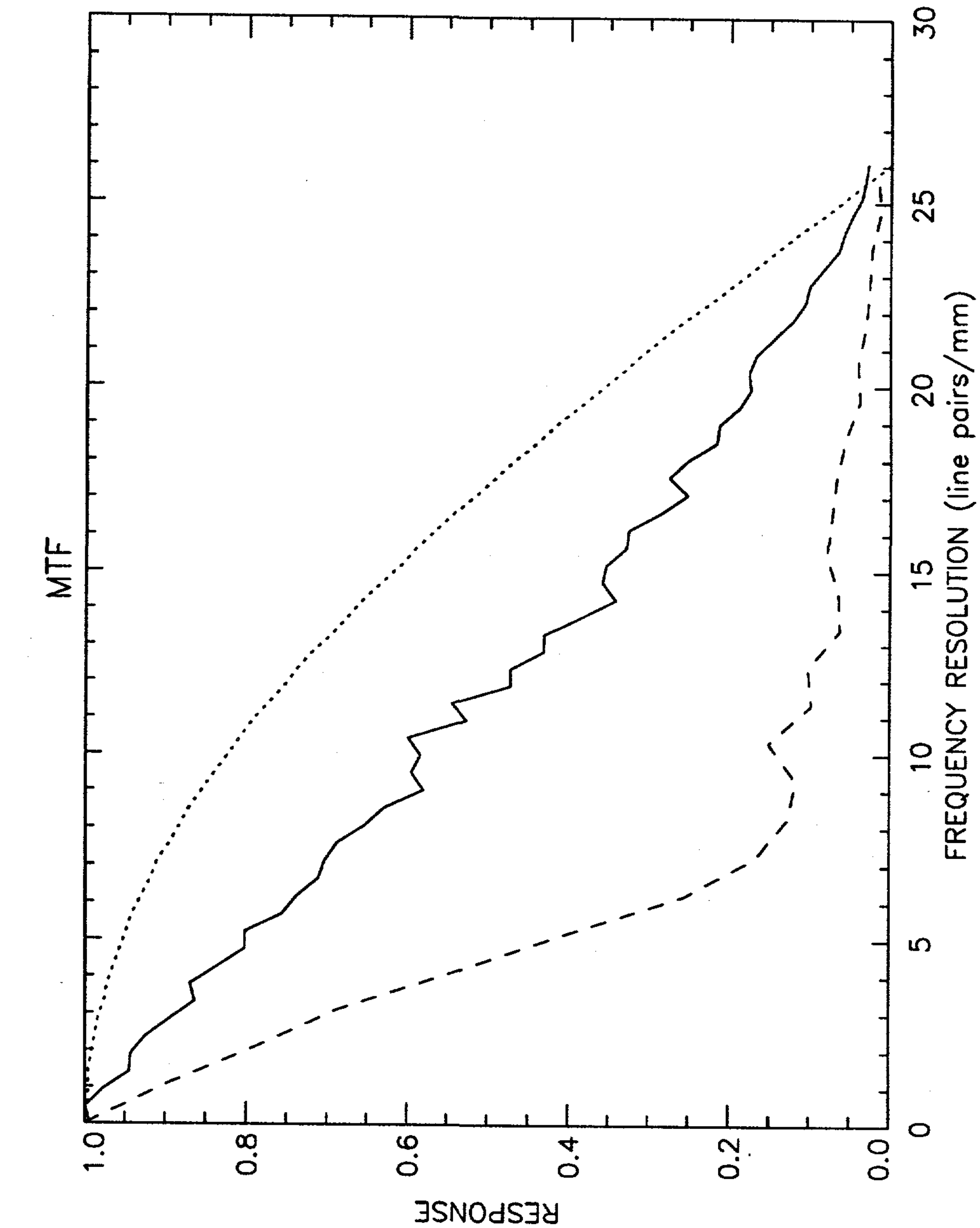


Figure 4


MTF
RESPONSE
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
FREQUENCY RESOLUTION (line pairs/mm)