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# Data Acquisition Systems for the Sloan Digital Sky Survey

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# Data Acquisition Systems for the Sloan Digital Sky Survey

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## ABSTRACT

The Sloan Digital Sky Survey (SDSS) will image Π steradians about the north galactic cap in five filters, and acquire one million spectra using a dedicated 2.5 meter telescope at the Apache Point Observatory in New Mexico.

We describe the data acquisition system for the survey's three main detectors: an imaging camera, mounting 54 Tektronix charge - coupled devices (CCD); a pair of spectrographs, each mounting a pair of CCDs; and a smaller monitor telescope camera. We describe the system's hardware and software architecture, and relate it to the survey's special requirements for high reliability and need to understand its instrumentation in order to produce a consistent survey over a five year period.

## 1.0 BACKGROUND

The SDSS is a collaborative effort between Fermi National Accelerator Laboratory (Fermilab), the University of Chicago, Princeton University, the Institute for Advanced Study, Johns Hopkins University, and the Japan Promotion Group. The survey will be conducted in the period 1995 - 2000. Its main results will be a photometric imaging survey and a red shift spectroscopic survey of galaxies and color selected quasars across a quarter of the sky about the North Galactic Cap. The imaging survey will consist of 10e12 bytes of data, from which we will extract the images of some 10e8 galaxies and 10e6 quasars. A million of the objects will be observed in the spectroscopic survey. Together, these data will allow the construction of a three dimensional map of the universe, whose volume is many times larger than the structures predicted by current theories of structure formation or observed in existing redshift surveys [1].

The SDSS is Fermilab's first collaboration in experimental astrophysics. Consequently, Fermilab may not be well known to the astronomical community. By way of introduction, Fermilab's primary mission is to operate the Tevatron, the world' s most powerful particle accelerator, and to assist in the undertaking of experiments in High Energy Physics (HEP) using its beam. The coming generation of HEP experiments at Fermilab will produce data at the rate of over 100 Mbytes/sec. Recently completed experiments have had data rates of up to 10 Mbyte/sec. However, Fermilab has long had an Astrophysics group, concentrating on theory. In 1991, Fermilab added the Experimental Astrophysics Group to its organization, and began its relationship with the Sloan Digital Sky Survey. Because of the high data rate (about 9 Mb/sec) of the SDSS imaging camera, it seemed natural for Fermilab to undertake the development of the DA systems for the SDSS. An internal collaboration between the Experimental Astrophysics Group and the Online Systems Department, which supports high-rate data acquisitions systems for HEP was formed to accomplish that task.

## 2.0 INSTRUMENTS

### 2.1 Cameras

Data Acquisition for the SDSS serves three types cameras. The Spectrograph and Monitor telescope have cameras mounting 4 and 1 CCDs, respectively, and do not impose any extraordinary system requirements[2]. However the SDSS CCD Camera, or imaging camera, depicted in figure 1, is an extraordinary instrument which integrates 54 CCDs, produces data at 9Mbyte/second, and dictates the overall requirements for the SDSS Data Acquisition systems.

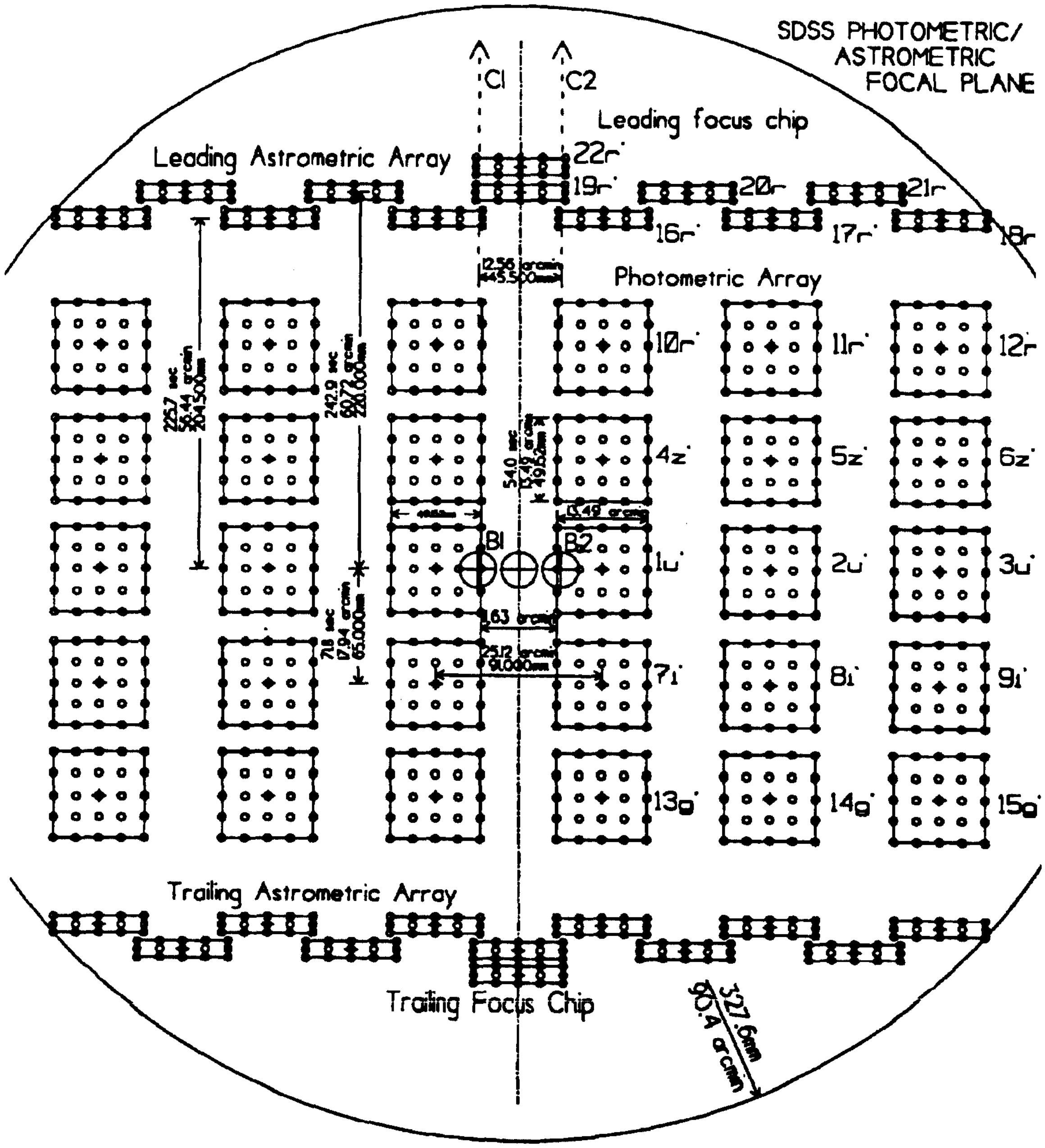


Figure 1 SDSS Imaging Camera

Two types of CCDs, performing three functions are mounted on the camera.

The photometric array makes up the central part of the imaging camera. It consists of 30 2048 x 2048 CCDs, arranged in 6 scan lines of 5 chips. A different filter is mounted in front of each CCD of a scan line, allowing simultaneous imaging in five colors. Repetition helps with the jargon: to image a three degree width sky of sky in five filters, it is necessary to make two Time delayed Integration (TDI) scans of twelve scan lines. The A/D conversion in the camera electronics has been carefully engineered to provide only the appropriate number of noise bits during conversion, enhancing the compressibility of the data.

The remaining CCDs are 2048x400 pixels. The leading astrometric array and trailing astrometric arrays are made up of two ranks of 2048x400 chips, which are covered with a neutral density filter. These chips will not saturate when imaging bright astrometric standards stars whose positions are well known.

Images from the two focus chips are mounted about 200 microns behind the focus. Half of each device will be covered by a window making it effectively above the focus. A comparison of images between the two halves will yield a differential measurement of the focus. For data handling purposes, pixels from a focus CCD are sometimes handled with those from its adjoining rank of astrometric CCDs.

The whole imaging camera is controlled over a serial line, and generates its own internal timing. After conversion, pixels are transmitted to the data acquisition system over 10 fibers: one fiber per scan line, and one fiber per rank of astrometric CCDs.

### 2.2 Telescopes

The 2.5 meter telescope imposes few requirements on the data acquisition system. Because of its accurate pointing and tracking the only feedback required is focus. The telescope are based on the successful Apache Point 3.5 meter telescope[3].

## 3.0 SYSTEM REQUIREMENTS

### 3.1 High Level Partitioning

In its original concept, the data from all survey instruments were to be reduced as part of the data acquisition process. This caused difficulties because the detailed requirements for data acquisition and data reduction conflict: The data acquisition system must be available in a robust form early in the commissioning of the survey, while the data processing system is allowed to evolve considerably during the system's test year. Equipment for the CPU-intensive data reduction must be specified at a relatively late date to secure cost advantage, while adequate equipment for the data acquisition system was available in 4Q92. The DAQ system can be developed early because its does not have a complex specification, while the data processing has a complex specification -- It proved necessary to build a prototype to understand various issues in its specification.

Early on, it was decided, as in HEP, to divide the system into two parts, a Survey Operations System (which includes the DA system) at Apache Point, and a Data Processing system to be located at Fermilab. The pain of writing a large amount of tape, and writing it redundantly, so that observing time is not lost should the data be lost in transit, was found to be offset by the simplification gained by the split.

### 3.2 Data Acquisition Requirements

The requirements which drive the system architecture are summarized as follows:

#### 3.2.1 Imaging

As mentioned above, the CCDs on the imaging camera fall into three classes: photometric, astrometric, and focus. There are different handling requirements for data from each class of device.

The photometric data is to be recorded in its totality, blocked into frames of 1354 rows from the CCD. This is 1/2 the distance, in rows between CCDs in a scan line, allowing the first frame from the second chip to contain an image of the same part of the sky as the third frame from the first chip, and so on. The frames are to be written to tape such that:

- All data from a single scan line are on the same tape
- Frames from corresponding parts of the sky are written together.
- Frames are to be written using the FITS standard.

Of course, in TDI integration, frame boundaries are quite artificial -- It is desirable to build a model of the flat field and point spread function (PSF) across the whole scan, and to have this model available for the reduction of the very first frame. To this end, the DA system builds two ancillary data sets from the CCD data. The first is quartiles of the distribution of the pixels in each column of each CCD for each frame. The second is postage stamps, a set of rectangular regions of pixels centered about a pixel which passes a simple thresholding test.

Quality Assurance (QA) requirements for the photometric system dictate that the images acquired over the last 45 minutes be maintained for inspection; access times for a given frame should be a few seconds. The quartiles and postage stamps must be maintained for quality analysis inspection over a night's observing. Additionally, the system must support the simultaneous display of images from at least one selected chip from each scan line.

All that is required of the astrometric data is that postage stamps be saved about pixels which pass a threshold. Normally, all pixels are not saved, and no quartiles need be computed, expect that whole images need to be occasionally written to tape for engineering and calibration purposes.

QA for the astrometric system dictates that 45 minutes of images be made available, just as for the photometric system. Additionally, the system must support the simultaneous display of images from at least one selected chip from each rank of astrometric chips.

Data from the focus chips needs to be collected, and a focus adjustment computed from the PSF of the detected images. Its QA requirements are as the astrometric system.

### 3.1.2 Spectrograph and Monitor Telescope Cameras

The requirements here are much simpler. The DA for these systems simply needs to keep up with the ADCs in the camera electronics, a few micro-seconds/pixel. The Monitor Telescope System must be a self-contained sub-system, for its deployment date (3Q94) is considerably ahead of the other two instruments(1Q95).

## 3.2 Control

The control features of all subsystems, along with all QA data are to be made available to a central control program, called Control Window (CW). A version of the program must run under a simple terminal interface, to allow diagnostics to be run by experts who may not be on-site. Several copies of CW may be run simultaneously; these copies must be made to cooperate in some fashion. The system needs to provide a number of programs indicating the status of operations: Quality Display (QD) and Quality Display with Graphics (QDG). The system must supply the compute power to run six such programs.

In addition to the data products mentioned above, a large set of instrumental parameters of interest are to be monitored, recorded, and maintained for the duration of the survey. To ensure consistency of the survey, changes to certain parameters are to be changed only under the supervision of a software system outside the data acquisition system known as Survey Strategy.

## 4.0 HIGH LEVEL HARDWARE ARCHITECTURE

It is our experience that it is best to partition a large Data Acquisition problem into a number of Host systems and Online systems. Host systems are a root of system control and user interface. Online Systems handle high-rate data flow.

Host systems run a friendly operating system (taken to be a UNIX like system). For the SDSS, this includes the CW, QD, QDG programs, and miscellaneous software performing high level functions. These functions inspect both summary data and a subset of the actual data originating on the camera, serve as the root of system control, and handle ancillary data streams. On these systems, nothing need happen with critical timing. Moreover, these systems are the locus of ad-hoc programming to diagnose failures, and gain an understanding of the detector.

Online computer systems handle the complete data stream from the detector, compute summary data, and serve subsets of the data to the host computer. Their computing resources are carefully matched to the problem at hand. Their software is written by experts, and is not subject to short-term change. These systems are supervised by a host, but do not depend on it for detailed intervention.

### 4.2 System Diagram

Figure 2 illustrates how these considerations lead the high level architecture of the SDSS DA systems. The figure is divided into three sections. The uppermost section illustrates other survey components with which the system needs to interface. The middle section, excluding S6 (Plate Handling) represent the DA system. The lower section represents external interfaces. Therefore, systems S1 through S5 plus all interfaces realize the SDSS data acquisition system. System S6 is not salient to this paper.

Since the Monitor Telescope is to be delivered and enter its test year well ahead of the spectrograph and imaging camera, a separate Host and online system(S1, S2) have been provided for it. These two systems control directly or indirectly all salient features related to the Monitor Telescope. When all survey instruments operate in tandem, These systems are slaved to the SDSS host computer system.

Distinct online systems are supplied for the spectrograph(S5) and imaging camera(S4), making the architecture somewhat more robust should the delivery of the instruments slip relative to one another. A single host computer(S3) serves for imaging and photometry, but a second temporary host could be supplied if the situation requires one.

### 4.3 High Level Features of Online Systems

To leverage the experience Fermilab has acquired building high rate systems for HEP, the online systems are built around a number VME backplanes connected by a VME interconnect; Disk and tape are integrated around SCSI bus. The software is built around a real-time kernel system (VxWorks) for determinism, lightweight process model, and ease of access to devices.

### 4.4 High Level Features of Host Systems

The host systems, of course, are off-the-shelf computers. The requirement, deriving from QA, to transfer large frames into these computers leads to the specification that these systems have VME interfaces. Each system is configured with several Gigabytes of disk. For compatibility with the SDSS Data processing systems, and to build upon experience gained in a prototype project, the Fermilab Drift Scan Camera[4] and to minimize the number of UNIX platforms to support, Silicon Graphics (SGI) systems were chosen, a 4D/35 with 112 Mb of memory for the Monitor Telescope Host Computer, and a Crimson with 256 Mb of memory for the SDSS host system.

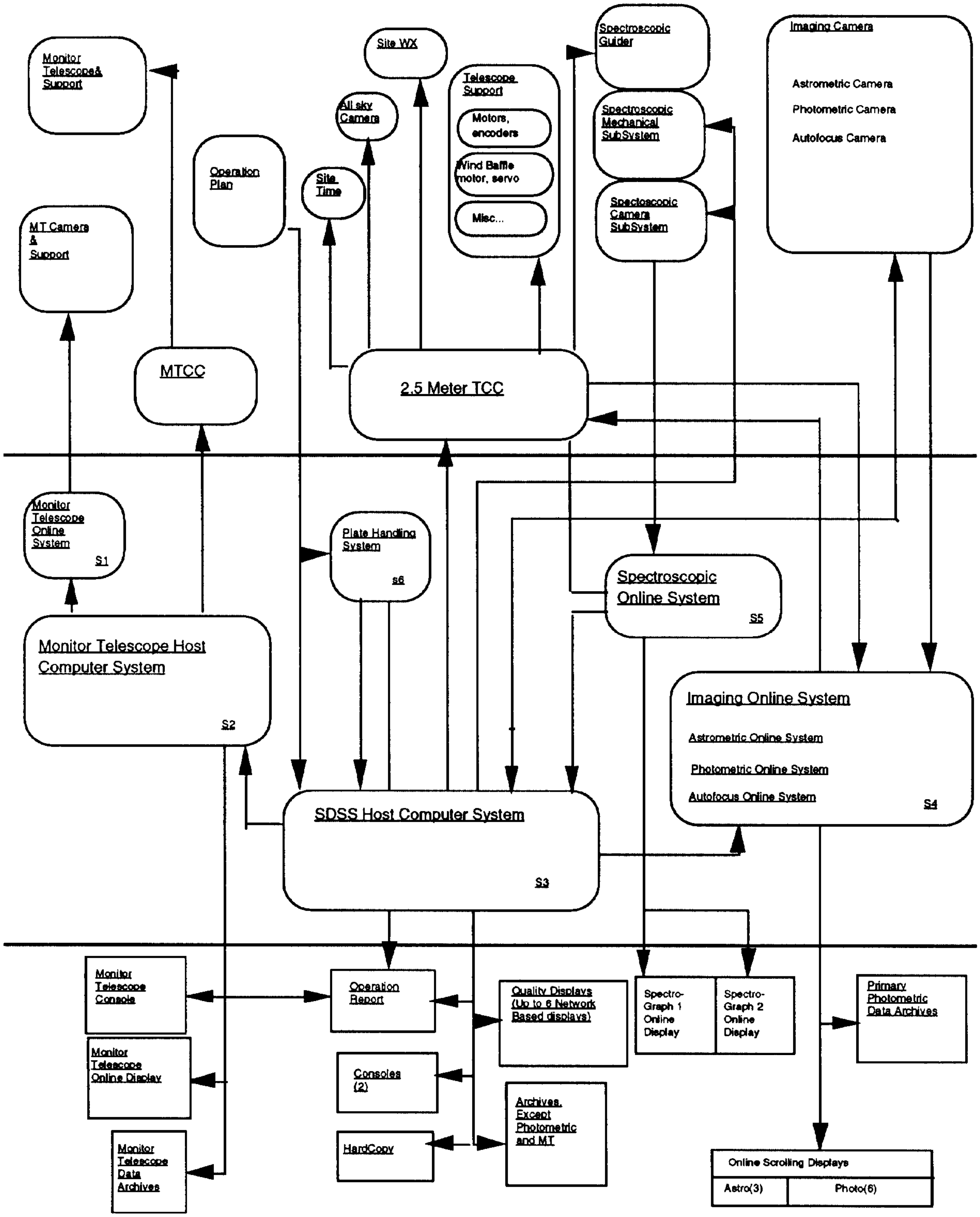


Figure 2 - Overview of Survey Operations

## 5.0 THE ONLINE SYSTEMS

To simplify sparing, and to reduce the amount of software effort required, all of the online systems are built around the same eight modules, and six interconnects. Figure 3 shows a configuration of these components in the Imaging Online System which services three scan lines of the photometric camera. The Imaging Online System is built around three of these VMEbus backplanes; The Spectroscopic Online System and Monitor Telescope Online System each have one similar backplane. The configuration of these VMEbus systems differs in detail.

### 5.1 Interconnects

5.1.1 The optical link from the camera (I1) -- All cameras transmit their pixels using the TAXI/FOXI system with a common data transfer protocol. Recall that the CCDs used in the imaging online system are run in TDI mode. Therefore, they are read-out through two amplifiers. The CCDs for the spectrograph and monitor telescope may be read out using 4 amplifiers. All cameras are built such that all CCDs are clocked simultaneously. We have specified a data transfer protocol where:

- The FOXI system is configured to transmit in 10-bit bytes.
- Each FOXI fiber handles data from up to 12 amplifiers.
- Each pixel is encoded in three such bytes, an amplifier number, most significant byte, least significant byte.
- An end of line byte signifies that all amplifiers have sent their data from the current line.

5.1.2 VMEbus, IEEE STD 1014 Rev D.(I2) -- This is a bus system which is well supported by industry. One can integrate high rate, special purpose computer systems using large number of commercially available CPU and peripheral cards. The cards purchased for the SDSS system, for example, support a block transfer mode, in which a 64-bit word may be transferred in well under 200 nanoseconds.

5.1.3 VMEbus High Performance Data Network(I3) -- This is a cable linking the online systems and host computers together. It supports data transfers rates in excess of 30 Mbyte/sec, more than enough to allow images to flow from the online systems to the host in the few seconds allowed for this task. An important feature of this interconnect is that all VME systems are bussed together, with room to add more crates. If necessary, we could add another host computer, or exotic systems add-ons, like a super-nova search.

5.1.4 Ethernet (I4) -- The ethernet is not used for critical data transfers during data acquisition. These take place over the VMEbus vertical interconnect. There are two reasons for this: A single ethernet cannot support the data rates envisioned in the system requirements; It is difficult to support the requirement that certain online systems continue should the host computer crash using the Internet family of protocols. Ethernet is used only to download programs across the systems, to pass error messages, and to receive telescope pointing information so the FITS headers can be filled out properly.

5.1.5 SCSIbus (I5) -- As mentioned above, SCSI is the peripheral bus of choice, because of the wide set of low cost peripherals available for it, and the large number of modules which support it. Scale drawings showed that it was easy to live with single-ended SCSI's 3 meter length limitation, and our tests showed that narrow, single ended SCSI would sustain instantaneous transfer rates of 5 MB/sec, sufficient for this system.

5.1.5 RGB Video Cable (I6) -- This Interconnect is more properly discussed in terms of the modules it interconnects. Suffice it to say, that these cables are long enough to span the distance between the computer room, where the DA system is located, to the operation room, which contain the displays.

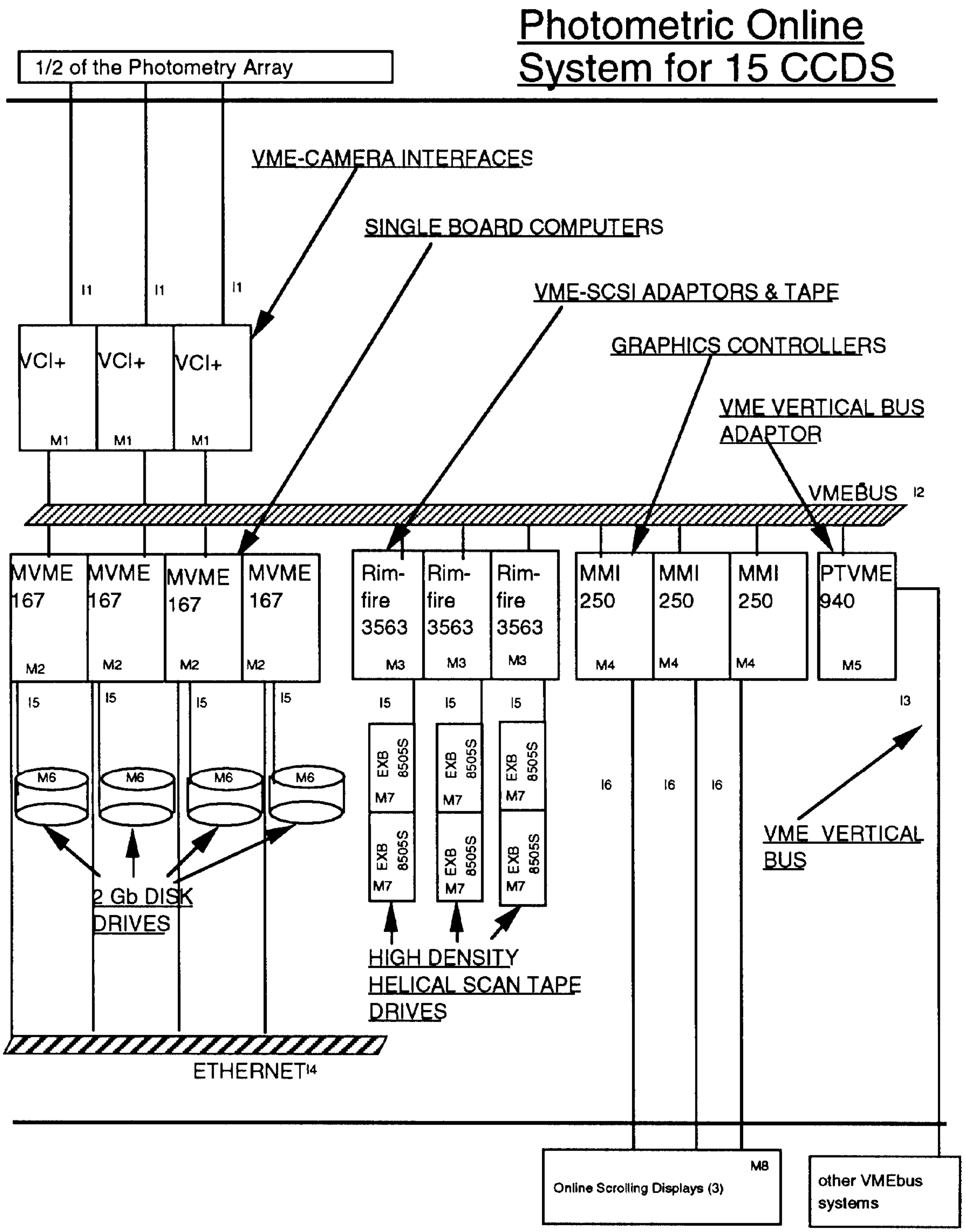


Figure 3- Online system for 15 CCDs

## 5.2 Modules

5.2.1 - VCI+ (M1) modules connects the Optical Data link from the camera and VMEbus. The VCI+ was designed and built at Fermilab, around a FOXI receiver, SRAM buffers, and a Xilinx field programmable gate array, since an appropriate commercial module was not available. The VCI+ maintains buffer areas for each corner of the CCDs it services. It places the pixels in the buffer area as they arrive. Each buffer area may be configured to place pixels in ascending or descending locations in buffer memory, to reverse the pixels from one side of the CCD with respect to the other. The buffer areas may be read over VMEbus. The module can be configured to generate an interrupt when a buffered line is available. A line from the buffer is flushed after both its POPA and POPB registers have been written to. This mechanism allows the data to be read out by two VMEbus computers without any other coordination mechanism.

5.2.2 - MVME167 (M2) is a VME single board computer. It is the workhorse of the online systems. The boards have a 33 MHz MC68040 and 32Mb of memory. An on-board DMA engine allows the computer to simultaneously acquire data and perform computations. This computer supervises all the tasks of the online system.

5.2.3 - Rimfire 3563 (M3) is a general purpose VMEbus to SCSIbus adapter. It accepts lists of buffers to write to tape, and returns an interrupt when finished. It provides some buffering, performing 32 bit block transfers over VMEbus, and driving a narrow, 8-bit SCSI bus.

5.2.4 -- Vigra MMI 250 (M4) is a VMEbus graphics controller, capable of driving a standard high resolution (1024 x 1280) color computer monitor. The boards have 4Mb of video memory, arranged as 2048x2048 eight bit pixels, and a 256-entry color lookup table (CLUT). These boards are simple: they do not have a programmable processor, but are quite capable of presenting a smoothly scrolling display of the sky while pixels are being acquired from the camera.

5.2.5 - Performance Computer Data Network Adapter Model 940(M5) is a VME master interface to the VMEbus high Performance Data network (I3). The card performs 32 and 64-bit block transfers while moving data from VMEbus to VMEbus, and may generate interrupts in remote crates.

5.2.6 - Micropolis 1921 Disk Drives(M6) a 2Gb, 5400 RPM disk drive, on which is realized a pool for temporary storage of the images, quartiles, and postage stamps. The VxWorks operating system allows data to be written to contiguous blocks, allowing good control of the timings, and meeting the specification that data may be written once, and read back twice even for worst-case thrashing while data acquisition is proceeding at full rate.

5.2.7 - Exabyte EXB8505S tape drives (M7) are 8mm helical scan tape drives for single ended SCSI. Fermilab has extensive experience with earlier Exabyte products, models 8200 and 8500. Several hundred of these are on site, and are the tape drive of choice in HEP. The 8505 is substantially different than earlier models: it is half-height and has a ceramic head. To date, the EXB8505S has proven more reliable than the earlier model EXABYTE drives in service at Fermilab.

5.2.8 - Nanao Flexscan Monitors (M8) are simple monitors meant for personal computers. They are capable of displaying a 1024 x 1280, eight-bit color image. Each monitor supports connections to two RGB cables, allowing the selection of an image using a front panel switch.

## 5.3 Online System Software

The Imaging Online System exemplifies how these system components work together. Figure 3 gives the configuration for half the data acquisition system for the photometry array. Three fibers feed into the system; each one contains data from a scan line on the camera: 10 corners of five amplifiers. Four MVME167s computers service the VCI+ modules, orchestrating the data acquisition.

At the end of each fiber is a VCI+, its shallow buffer memory configured into ten buffers. Pixels from the right half of the CCDs are loaded into the buffer memories in ascending order, pixels from the left half in descending order. When the end-of-line byte is received from the camera each VCI+ board generates two VMEbus interrupts, for each MVME167 board has enough CPU power to service only four CCD's worth of data.

On receipt of the interrupt, the MVME 167 boards initiate a Direct Memory Access (DMA) transfer of the appropriate pixels from the VCI+ into a small buffer area in their memories. When the transfer is complete, they signal the VCI+ board to free the buffer area, to be re-filled with pixels from another line. This signaling is done by writing one of two distinct VMEbus addresses. The buffer area is flushed when both locations are written to. In this way, the VCI+ board synchronizes the two computers.

After each such interrupt the MVME167 carries out four operations on a small circular buffer containing pixels from the last few lines acquired.

- The pixel frequency histogram for each column is updated, so that quartiles may be calculated.
- A line is searched using a simple thresholding algorithm, and postage stamps cut out if appropriate.
- If those pixels are to be displayed on a scrolling display, they are mapped to 8-bits and transferred to the VIGRA board using the DMA feature of the MVME167.
- The lines are compressed, and moved into a buffer, to be written to disk. When full, the disk buffer is marked for write, and replaced with a fresh buffer. The result is that the compressed pixels are stored on disk as a FITS binary tables.

When a frame's worth of data has been acquired, the histogram and disk buffers are replaced with fresh buffers. In a separate task, and asynchronously to the line-by-line read out of the VCI+ described above, quartiles are computed from the histograms, and all data products: quartiles, compressed images, and postage stamps are staged to disk.

Several other activities occur asynchronously on the board:

1) An archiver task reads the FITS files holding the image data into buffers and programs the RIMFIRE 3563 to spool them to tape. The FITS files are re-organized, so that corresponding parts of the sky are logged to adjacent bits of the tape. The data are archived redundantly. Archive tasks on two MVME167s are involved in writing a redundant set of tapes. They are coordinated using software, as they need to interact only every few seconds.

2) The MVME167 boards serve the quartiles, postage stamps and images to the SDSS host computer. A data serving task listens for requests arriving over the VMEbus, transfers the requested data into a buffer area, and programs the PTVME 940 board to deposit the data into a buffer in the host's memory.

3) A command server listens for general control messages.

4) A scrolling display task is interrupted by the VIGRA board 72 times a second, and advances the scrolling display the appropriate number of lines.

Additionally, each MVME167 maintains a status database in its local memory. A status entry is identified by an alphanumeric name, a type (integer, floating point, etc.), the actual, minimum and maximum values, and a description, protection (who can change it) and current validity. Each node maintains about 150 parameters. The host computer may read these locations to obtain information required for its operation.

Finally, the online systems can report error and status to the host computer over the ethernet using the Fermilab MURMUR package, which is best characterized by mentioning that it both displays urgent messages to observers and records significant events into a log file.

## 6.0 THE HOST SYSTEMS

The host system serve as the root of system control. As such, their software environment is their most interesting feature. It is best to begin by describing the survey standard software tools kits which have been incorporated into its construction. Many of the common tools are described in [5].

### 6.1 Baseline tools

SHIVA (survey Human Interface and Visualization Environment) [6] is the tool kit used for supporting the real-time analysis of acquired data. As discussed above, data acquired are assembled into frames. For detailed viewing and analysis, frames are copied into Shiva regions. Shiva provides C and TCL framework to access these regions. Shiva was developed, in part, by integrating:

- PGPLOT: a package for drawing simple scientific graphs on various displays; it was developed at Caltech[7].

- FSAOIMAGE: an X11 window based, interactive, color or halftone image display program for astronomical images adapted from the venerable SAOImage package[8], developed at the Smithsonian Astrophysical Observatory.

- FTCL: A Fermilab packaging of Tcl/Tk[9]. We have added command line help, command line editing integrated with the Tk event loop, and other added value features, and packaged Neosoft's extended TCL package[10]. We run the TCL system under VxWorks in the online systems as well using a port from NOAO[11][12].

- LIBFITS: A procedure call package, developed by Alan Uomoto of Johns Hopkins University[13]

Help and documentation is built upon the WWW wide-area hypermedia information retrieval system developed at CERN [14]. Information browsing is supplemented by the Mosaic browser developed at the National Center of Supercomputer Applications (NCSA) [15].

Data base management is based on a commercial Object oriented data base, VERSANT[16]. A discussion of this tool beyond the scope of this paper. This system is used to keep track of a number of operational data.

Error messages and log files are kept using the Fermilab MURMUR software tool[17].

### 6.2 Applications

Nearly all of the survey's software is built around the Tool Command Language (TCL) developed at the University of California, Berkeley by John Ousterhaut, et. al) Tcl is a C and Lisp-like user extensible command interpreter. One writes command primitives in C, and declare them to a TCL interpreter. Observing programs can be constructed in TCL from these primitives. Because other survey software has been written for TCL, it is possible to re-use other primitives related to image display, databases and so forth. Because TCL itself can be used in a simple way over a terminal line, simple, functional Observer's programs can be constructed. These can be fitted with fancy X-window screens at a late date, after the system's basic integration is proven.

The observer can construct any number of Tcl Procedures to control any aspect of the data acquisition and analysis. One Tcl procedure may refer to another giving the observer considerable power. Other TCL scripts control the tape archiving, and call up frames from the online systems, uncompress, and display them.

Because TCL runs in the Online system, many system control messages are basically passed TCL messages, done in the manner of fanned out remote procedure calls. Commands come in three classes: those that may execute only in the online system, only on the host, or both.

## 7.0 PROGRESS TO DATE

The DAQ systems have been purchased and are physically installed at Fermilab. The core software system is complete: The Monitor Telescope systems are ready for deployment at Apache Point, NM. and awaits the delivery of the telescope. A prototype system, the Fermilab Drift Scan Camera is deployed at Yerkes Observatory in Wisconsin.

Survey specific observer's programs need to be written for the SDSS host computer. The VCI+ module is in debug, the Online systems are being adapted to read-out several CCDs using it. We need to adapt our Exabyte driver from Rimfire 3515 adapter to the 3563 adapters, and build the archiver task, and adapt our Online display driver to display bits of images from several CCDs simultaneously. The system needs to be put into mock operation to prove out its reliability, in time to integrate with the survey's instruments late this year and early next year; we are building a camera simulator powerful enough to drive one crate of the imaging system.

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