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Optimization of a Microprocessor-based Line Reversal System for Temperature Measurements in Coal Combustion Plasmas

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Kim Nelson

August 1989

ACKNOWLEDGMENTS

I wish to express by sincere gratitude to my thesis advisor, Dr. Tom Giel, and my supervisor, Mr. Brad Winkleman, for their guidance and never-ceasing willingness to help me. They provided the opportunity to work and study at UTSI.

Also, I wish to thank my family and friends for the constant support and prodding necessary for me to complete this project. I have gained and grown so much from associating with them that it is impossible to cite all the instances. In particular, I would like to mention my parents, Roland and Jean Nelson, and my best friend, Miss Selena Espy. Their support has been vital to me.

Most of all, I must give thanks to my God, who constantly gives me the grace to continue.

ABSTRACT

The absolute, radiometric, plasma temperature measurement method of modified line reversal (MLR) is reviewed briefly with respect to its components and use at the U.S. Department of Energy Coal-Fired Flow Facility (DOE CFFF) at The University of Tennessee Space Institute. Performance of the existing system is discussed. A survey of the existing electronics, physical layout and operations of the instruments, including the data acquisition and analysis equipment concludes that the existing system is severely limited in its ability to address additional anticipated plasma temperature measurement needs at the CFFF. Many of the existing system's limitations are due to dependence on the CFFF mainframe minicomputers for data acquisition and processing. To address many of the limitations, a general-purpose, commercially available microcomputer was chosen as the base of the new, stand-alone data system. Several hardware devices were assembled with the microcomputer: a data acquisition/multifunction board, a DMA card, a GPIB standard interface bus, and a 45 MB removable hard disk drive. The software environment for the acquisition, calculation and data management were programmed using a graphical programming language based on principles of dataflow processing. The microprocessor-based, stand-alone MLR system was subsequently developed and was tested using prerecorded, analog MLR signals.

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CHAPTER 1 -- INTRODUCTION

For several years, a modified line reversal (MLR) system has been used for plasma temperature measurement at the U.S. Department of Energy Magnetohydrodynamic (MHD) Coal-Fired Flow Facility (CFFF) at the University of Tennessee Space Institute (UTSI), Tullahoma, Tennessee. The method of MLR involves measuring the spectral radiant flux density (SRFD) of a high temperature emissive gas and that of a reference source as seen through that gas. This is done by collimating and focusing a reference light source of known wavelength through the plasma and onto a photo-sensitive device (photodetector) which, in turn, converts the resulting SRFDs to voltages. The wavelength is selected to correspond to an emission line of a species in the gas. Often the sodium or potassium D lines are used, thus giving MLR the common names of sodium line reversal and potassium line reversal. Since both the radiating gas and reference sources are usually focused onto the same detecting instrument, there must be a way to distinguish between the gas and gas plus reference SRFDs. Signal separation is the process by which the SRFDs are differentiated.

Although several signal separation schemes exists[2,7] UTSI uses only two schemes. The first is optical-spatially, where the reference and plasma images are focused onto a face-plate containing two adjacent photodetectors.[3] The optics produce focused images such that the reference lamp image is concentric within a larger gas image. On the detector face, one photodetector corresponds to the approximate center of the two images or 'gas plus reference lamp' image. The other photodetector lies in a region where the gas image alone falls. Since UTSI uses line reversal in MHD research at the CFFF, the hot emissive gas is generally a plasma and will be referred to as a plasma, resulting in the names plasma plus lamp (PL + L) and plasma alone (PL) images. This optical-spacial signal separation scheme is illustrated in figure 1.1. Within the detector housing, the converted signals are amplified separately with matched amplifiers and transmitted for digitization at individual output terminals.

The second signal separation scheme used at UTSI is electro-mechanically, a process in which the reference source is chopped (blocked) at a set, known frequency (approximately 1 KHz) before it is collimated and transmitted across the plasma, resulting in an alternating PL + L and PL image. The image is focused on the face-plate of a single photodetector. This instrument differs from the previous instrument in that the alternating incident SRFDs are converted into an alternating voltage which is amplified and output ('multiplexed') on one set of terminals. Normally, the output is directly introduced to a signal separation circuit, which uses a TTL-compatible signal from the chopper's controller to separate the one analog signal into its two components. Figure 1.2 illustrates this signal separation scheme.

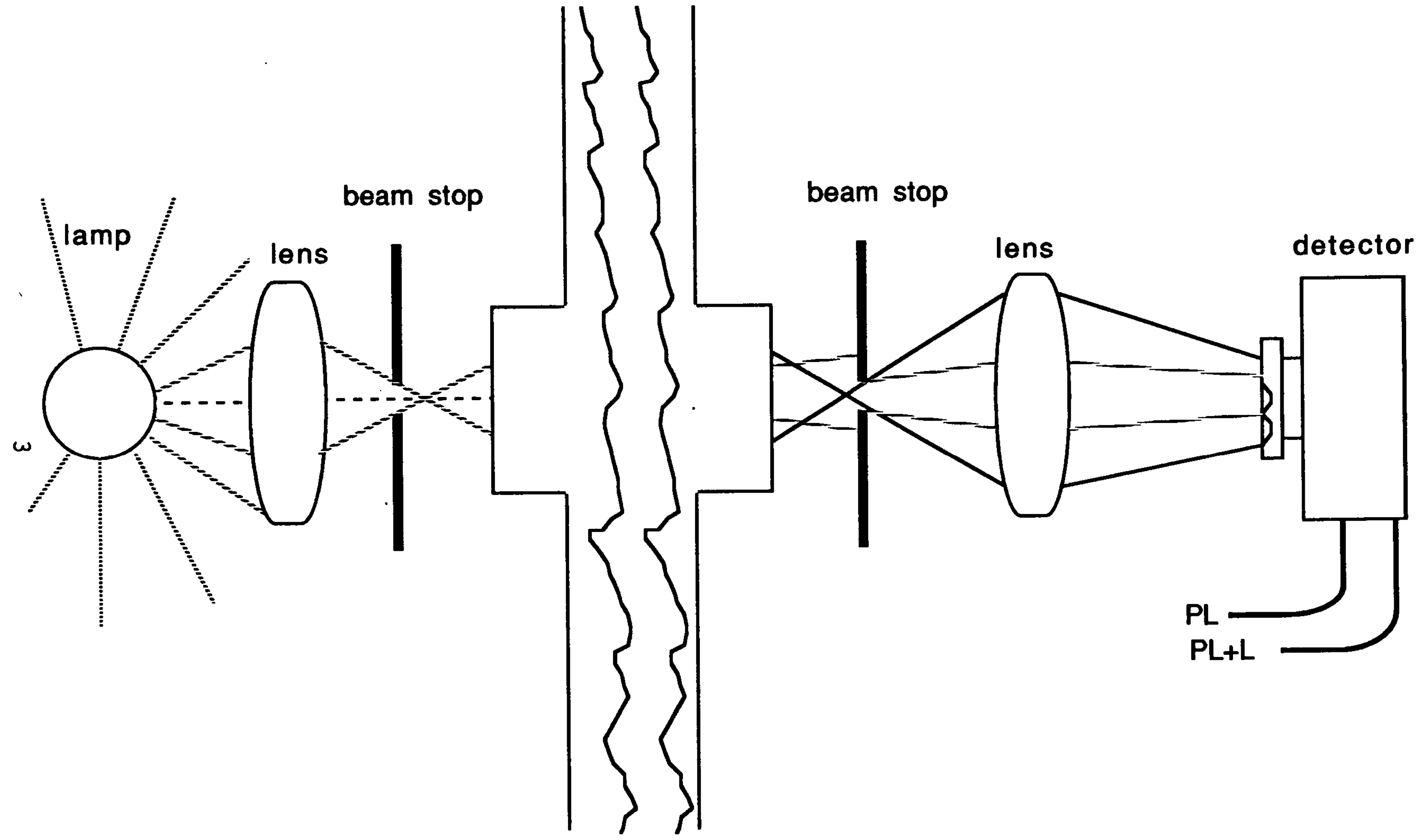

Figure 1.1 Diagram of Optical-Spacial Separation

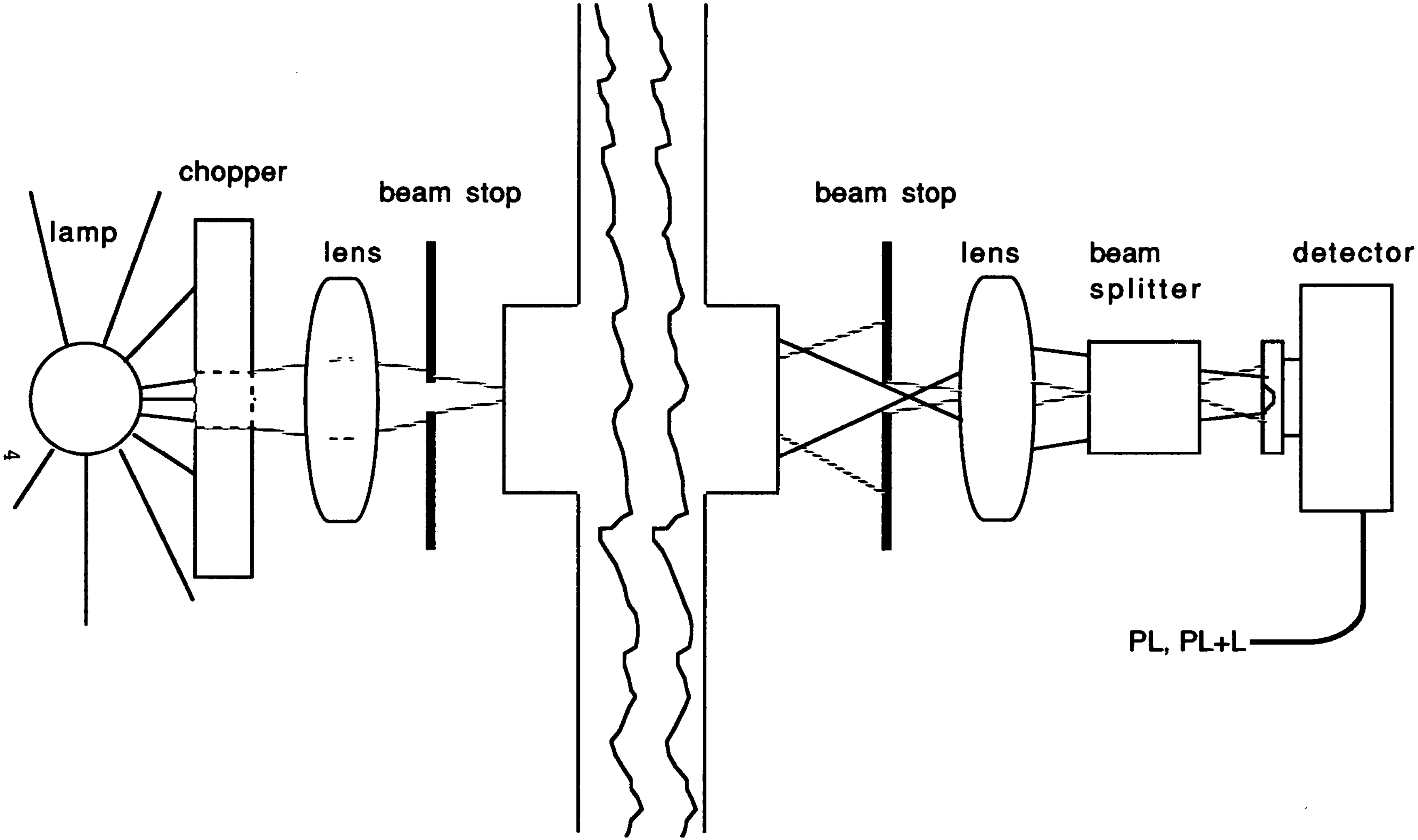

Figure 1.2 Diagram of Electro-Mechanical Separation

The two separation schemes described thus far each possess characteristic errors that should be noted. First, the optical-spacial method has an inherent spatial error because the two radiation sources use slightly different optical paths. Therefore, the measured plasma volume is not totally common to both radiation sources. This particular error is discussed in Winkleman.[1] Second, the electro-mechanical method is subject to temporal errors. Since the reference lamp is chopped, the PL and PL + L signals are sequential. Because of the form of the line reversal formula, each measurement is needed for one temperature calculation. As a result, the temporal errors exist because the two measurements do not describe the conditions of the plasma at exactly the same time. A full treatment of this error is done in Winkleman.[3]

Line reversal techniques are quite important and common to plasma temperature measurement due to the very high operating temperatures, 1900°K to 3500°K, encountered therein. MLR is particularly vital to plasma temperature measurements in coal-fired MHD systems because of the slag species in coal-fired plasmas and the highly erosive and corrosive nature of the plasma itself in addition to the high gas temperatures. Even if an instrument were to be properly protected against the thermal and corrosive effects of the plasma, molten slag, the mixture of incombustibles from coal, would present a major problem. Slag has the unfortunate characteristic of clinging to any surface cooler than itself. Of course, any material clinging or solidifying onto a temperature probe would insulate the probe and disturb the gas flow around the object, thereby changing the probe heating by radiation and convection. Unchecked, the probe may become totally insulated by slag. It is evident that any physically intrusive temperature measurement device would be coated with slag or destroyed in the temperature regime previously mentioned. Generally, spectroscopic methods such as MLR do not experience any of the problems previously mentioned. Optical approaches are not as limited by high temperatures as physical probes are, and, with the exception of occasional blocking of optical ports, are not effected by slag. For these reasons, the MLR spectroscopic technique is currently the most attractive way of measuring high temperatures in a coal-fired MHD environment.

Since its development by Vasil'eva at the USSR Institute of High Temperatures,[1] there has been much work done on the development of modified line reversal methods for MHD plasma temperature measurement. V. B. Novosudov investigated errors arising from photomultiplier noise and the focusing of the optical system, and B. C. Winkleman has studied effects of the optical imaging system, errors due to the measured plasma's temporal non-isothermal character, and effects of slag in the plasma flow stream.[1,14] J. W. Daily has scrutinized the effects of turbulence.[4] J. W. Daily and C. H. Kruger have examined the effects of a spatially non-isothermal plasma with cooled walls and a hot core and colder boundary layers.[5] The resulting non-linear line of sight averaging has been investigated at Stanford University[30] to define criteria for measuring the core temperature. Particle emissions, absorption, and induced scattering errors have been studied and a scheme to correct for these effects was developed at Mississippi State University.[6] These areas represent only a sampling of the work done to improve modified line reversal methods for coal-fired MHD development, and will not be further addressed here.

Even with the large amount of theoretical work which has been done on line reversal, there is much that still can be done to unencumber its application at the DOE facility at UTSI. Operationally, the CFFF systems have several problems: relatively high maintenance requirements of the detectors, low frequency response of the systems, laborious calibration requirements, significant electronic drift over very long-term use required to accommodate the long CFFF tests, and the ominously familiar problem of slag, to name a few. Still, the most limiting problem for the CFFF is the immobility of the line reversal system itself.

As of March 1989, all data acquisition and calculations at the CFFF are done using one of three Data General mainframe computers. Obviously, any system dependent on a mainframe computer cannot be very mobile. In chapter 2 it will be shown that mainframe dependence also gives rise to low frequency response and tedious calibration procedures as well as the inconvenient addition of supplemental detectors. In addition, with requirements for line reversal measurements at multiple, different locations, the system must be mobile and autonomous enough to perform the necessary line reversal signal acquisition, processing and data calculation. As the organization of the system unfolds, it is seen that the best way to improve the system is to base it upon a dedicated, portable processor.

By introducing an independent processor for line reversal operations, the facility's mainframes are relieved of the data acquisition and calculations involved in line reversal temperature determinations. Conversely, line reversal operations upon an independent processor would not be hampered by limitations of the mainframes, such as prescribed low sampling rates and lack of opportunity to modify software parameters as test conditions change during hundreds of hours of continuous testing. The biggest advantage, though, is in the possibilities to further the capabilities of the system. With a dedicated processor, there would be flexibility to explore high frequency phenomena associated with the transonic MHD generator plasma flow. Wavelength scanning capabilities could be vastly improved, allowing high frequency particulate corrections to be incorporated using the Mississippi State University technique.[6] Sodium or potassium levels could be measured as well if wavelength scanning capabilities are added.[6] Calibration could be automated, and the need for human intervention reduced. All these things are either exceedingly difficult or impossible with a facility mainframe-based system.

Throughout the remainder of the paper, the existing systems and circuits are reviewed. System operation, calibration, and data acquisition and management are discussed, particularly in how they are handled in a facility-based versus in a stand-alone environment. Schemes of providing a stand-alone habitat for line reversal (i.e. Buy or build? What processor/computer would be acceptable?) are examined economically and technically. Based on this examination, a stand-alone MLR data system configuration is suggested and developed. Finally, the new system is verified using analog recordings of potassium line reversal SRFDs from a past Low Mass Flow (LMF4) test of the DOE coal-fired flow facility at UTSI.

CHAPTER 2 -- EXISTING EQUIPMENT AND SYSTEMS

There are four major sections to the modified line reversal system: optics (including the reference lamp, lenses, stops, ports, apertures and mounting equipment), detectors, signal separation equipment, and the data handling/processing sections. Each section exists, in some shape or form, in both the chopped and continuous signal types of line reversal systems operated at the CFFF. Unfortunately, most of the problem areas for each section are common to both system types.

The optical section

The optical section for electro-mechanical signal separation is shown in figure 2.1 and is comprised of a tungsten strip reference lamp followed by an electro-mechanical chopper, a collimating lens and a beam stop. The previous elements hereafter are referred to as the "lamp side" of the system. The lamp itself is calibrated at selected spectral radiances at several wavelengths which allows operation of the lamp at known brightness temperatures. Quarter-inch thick quartz windows are mounted on standard, three-inch Babcock & Wilcock, Inc. optical ports on either side of the plasma ducting, which in this particular case happens to be on the diffuser section near the entrance to the primary furnace, the section marked EM on figure 2.2. The "detector side" is composed of a second beam stop followed by a focusing lens and terminated with a detector. The detector referred to may be a single-wavelength photodiode detector

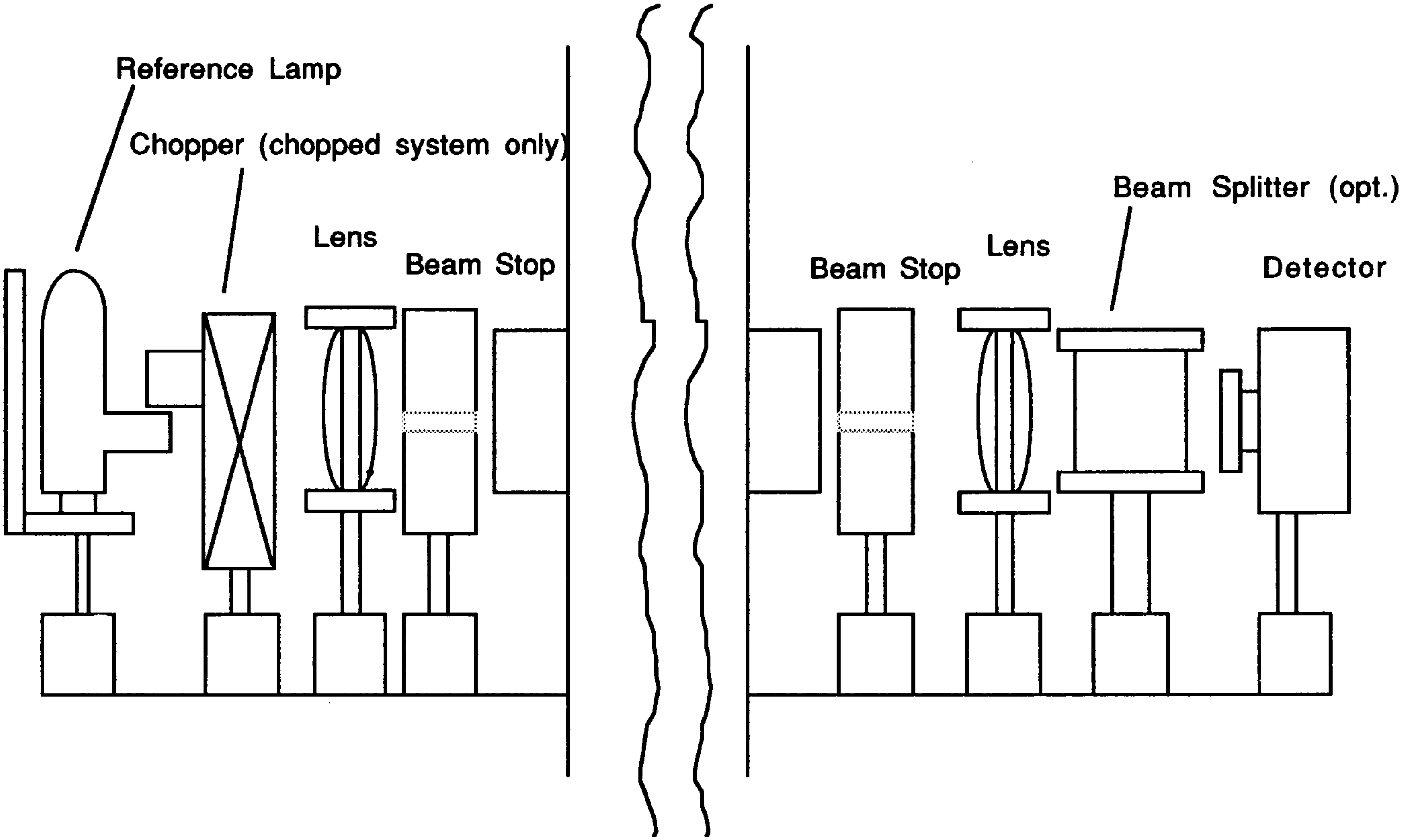

Figure 2.1 Schematic of Optical Components

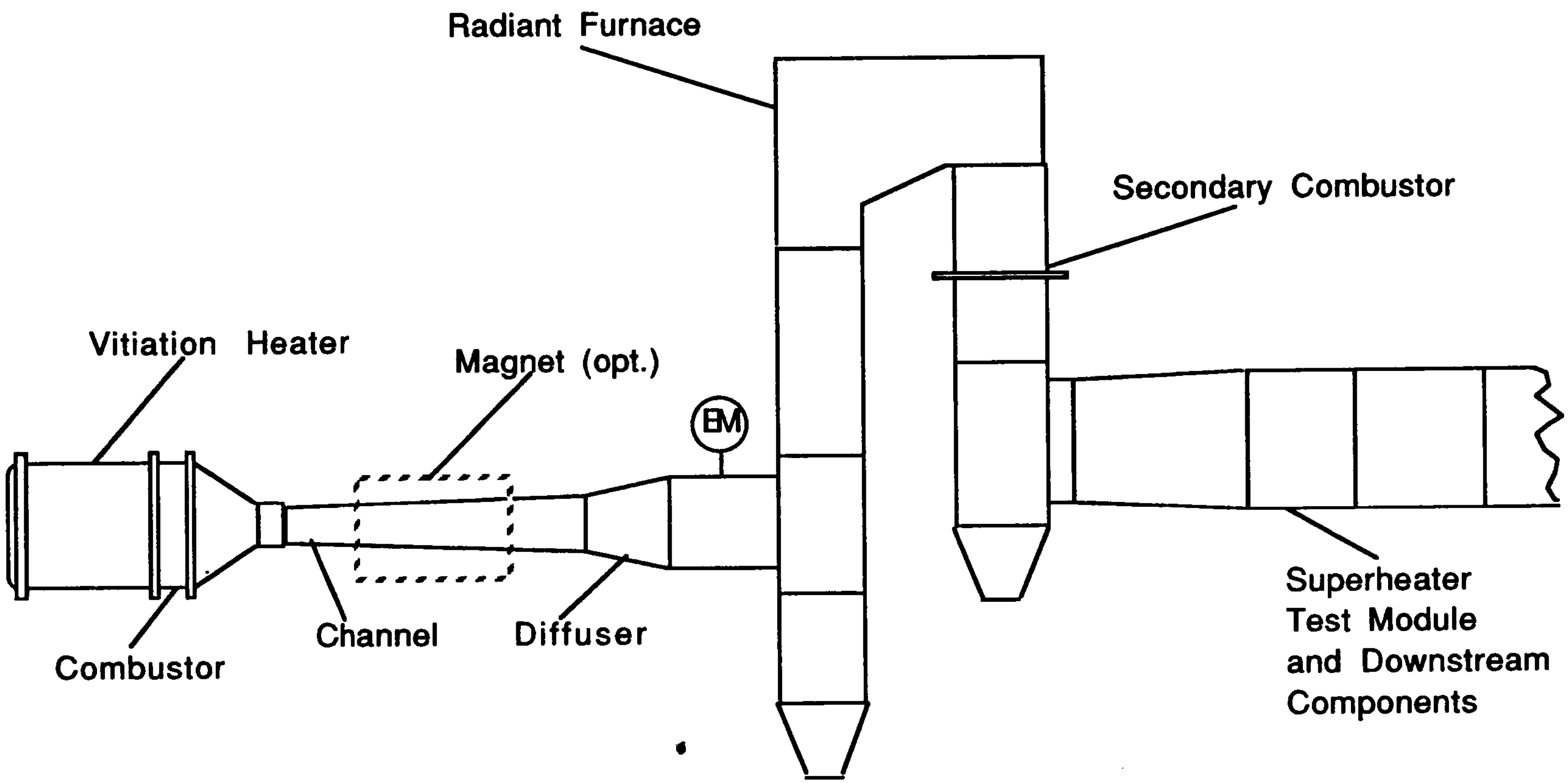

Figure 2.2 View of DOE LMF4 CFFF Flow Train
*Upstream Sections

or a multiple-wavelength scanning monochrometer. At the diffuser location both are usually simultaneously employed with the chopped signal separation system by using a beam splitter following the focusing lens. The position and diameters of the detectors, apertures and lenses are selected to provide fully lit lamp and plasma images that completely cover the detectors. The optical section for the optical-spatial signal separation is nearly identical except that the chopper is not employed and two adjacent detectors replace the single detector. These adjacent detectors are commonly photodiodes mounted behind narrow-bandpass optical filters, but an optical multichannel analyzer array in the monochrometer/spectrometer is also a possible detector.

There are relatively few problems with the optical system. Slag is still an ominous fiend. As the previous chapter points out, spectroscopic methods are not generally degraded in performance due to the effects of slag except in the blockage of the optical ports into the flow ducting. Currently, when excessive slagging occurs, the port must be quickly reamed with a metal pipe. This method subjects the MLR operators to some health risks as well as disrupts the measurement for a time. Currently, the design of a valve-actuated port sleeve is being considered for an automatic port clearing device.

Detectors

As stated previously, two types of instruments are currently used for line reversal detectors at the CFFF. A SPEX model 1870 spectrometer, manufactured by SPEX Industries, is the first one. The spectrometer may be used as a monochrometer to monitor a single spectral line, scan a number of them, or simultaneously monitor several lines using an optical multichannel analyzer. A vibrating mirror assembly in the monochrometer allows rapid alternating detection of 2 spectral lines. The second line reversal detector is based upon amplified photodiode signals. It is these detectors which the MLR stand-alone system is most concerned with. The photodiode detectors are used to make DC measurements of the amplitude of a single spectral line or spectral region of radiation incident to it. At this time, two versions of the same circuit are used for the photodiode-based detector. Figure 2.3 is a general block diagram of the photodiode detector's operation.

The existing circuits both use an EG&G HUV 1100BQ photodiode as the foundation of the detector, preceeded by an optical bandpass filter whose passband is a maximum at 749.9 nm with a half-intensity bandwidth of .85 nm. The filter determines how wide the spectral sensitivity of the detector is going to be. The emission line being measured must encompass all of the filter passband for true line reversal measurements to be accomplished. Generally, in coal-fired MHD systems, where potassium is added as the ionizing "seed" species, the potassium doublet lines are each 50 to 100 nm in width.[7] Self reversal of the line centers at 766.5 nm and 769.9 nm, due to strong absorption of the hot core emissions by the cooler boundary layer, does not extend to the 749.9 nm filter passband center. The HUV

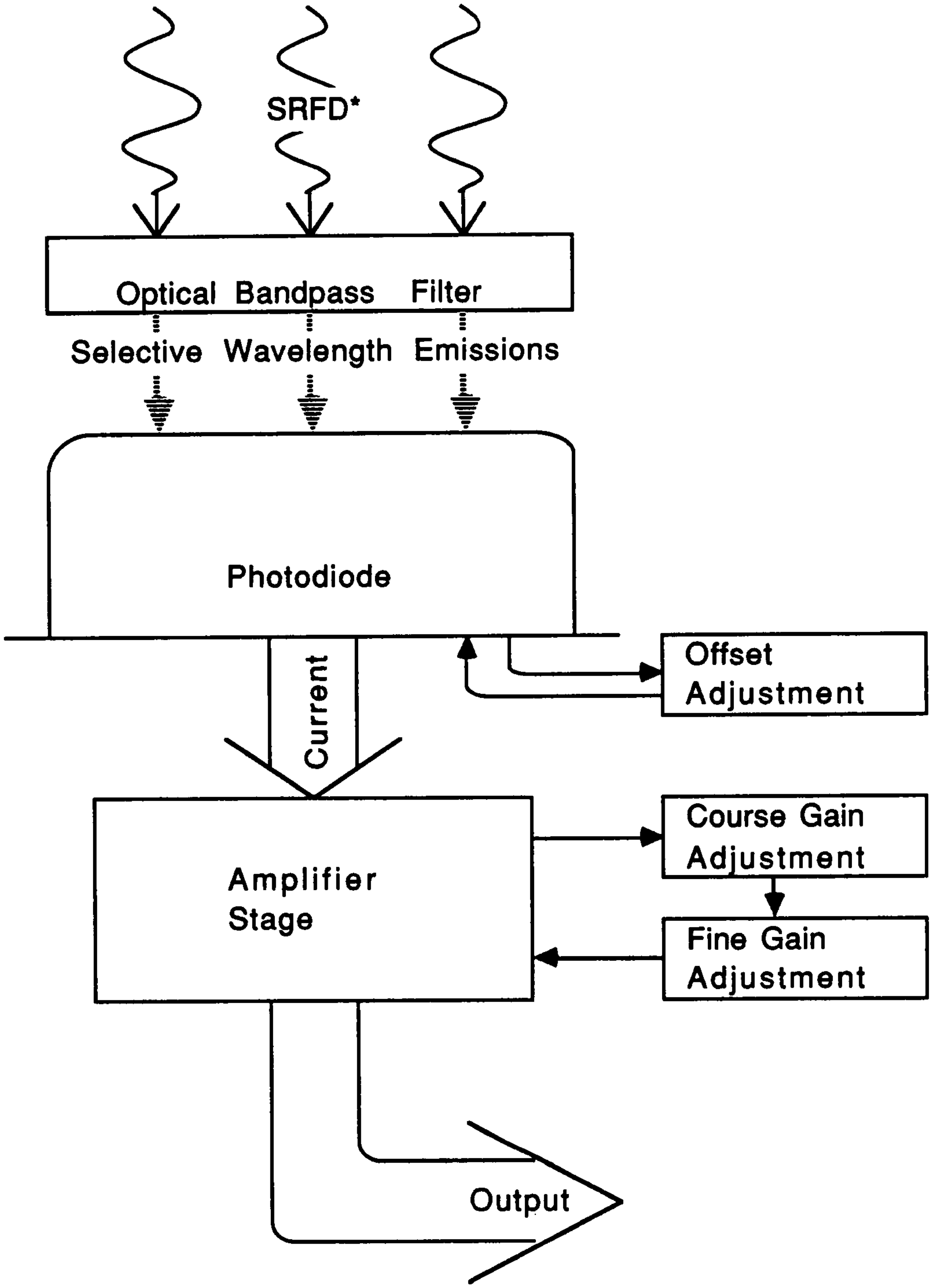

Figure 2.3 Block Diagram of MLR Detector Operation

* Note that this is one photodetector/amplifier pair. For optical-spatial separation, there will be two of these.

1100BQ is a photodiode made up of a silicon detector and a close coupled low-noise amplifier in a TO-5 package. While it is not a fast photodiode (its slew rate is 12 volts per 10 μsec), its spectral response is very nearly linear and is relatively high (about 0.53 A/W) in the 750nm potassium doublet region at 23°C.

Figure 2.4 shows both circuits (denoted A and B) used to amplify the photodiode output. In both current circuits the power for the photodiode and the rest of the circuit is supplied by a 115 VAC input, $\pm$15 VDC, 350 mA output potted power supply. The $\pm$15 volt lines are filtered at the photodiode by an RC combination. The -5 volts necessary for the rest of the circuit is supplied by a 7905, negative 5-volt supply voltage regulator. The regulator's lines are filtered by small capacitors.

Analog Devices AD522 and AD521 instrumentation amplifiers are used in the amplifier stages of versions A and B, respectively. The AD521 is a second generation, monolithic IC with programmable I/O gain, where the AD522 is a hybrid chip with the same functions. Version A, the first of the two circuits, uses a 22K-ohm resistor in series with a 10K and 1K potentiometer, which are the course and fine gain adjustments, respectively, for the detector. Upon output from the AD522 amplifier, the signal is routed directly to the instrument's output terminals. The second version, B, possesses a two-stage amplifier circuit. The course and fine gain adjustments are 5K and 1K-ohms, respectively, and are in series with a 100-ohm resistor on this board. The AD521 is followed directly by an LF356,

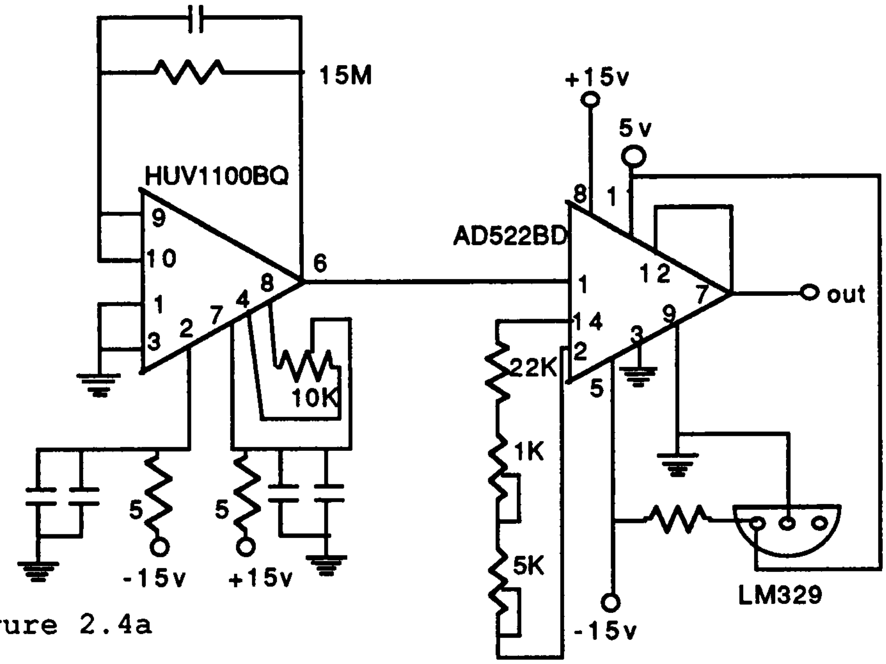

Figure 2.4a

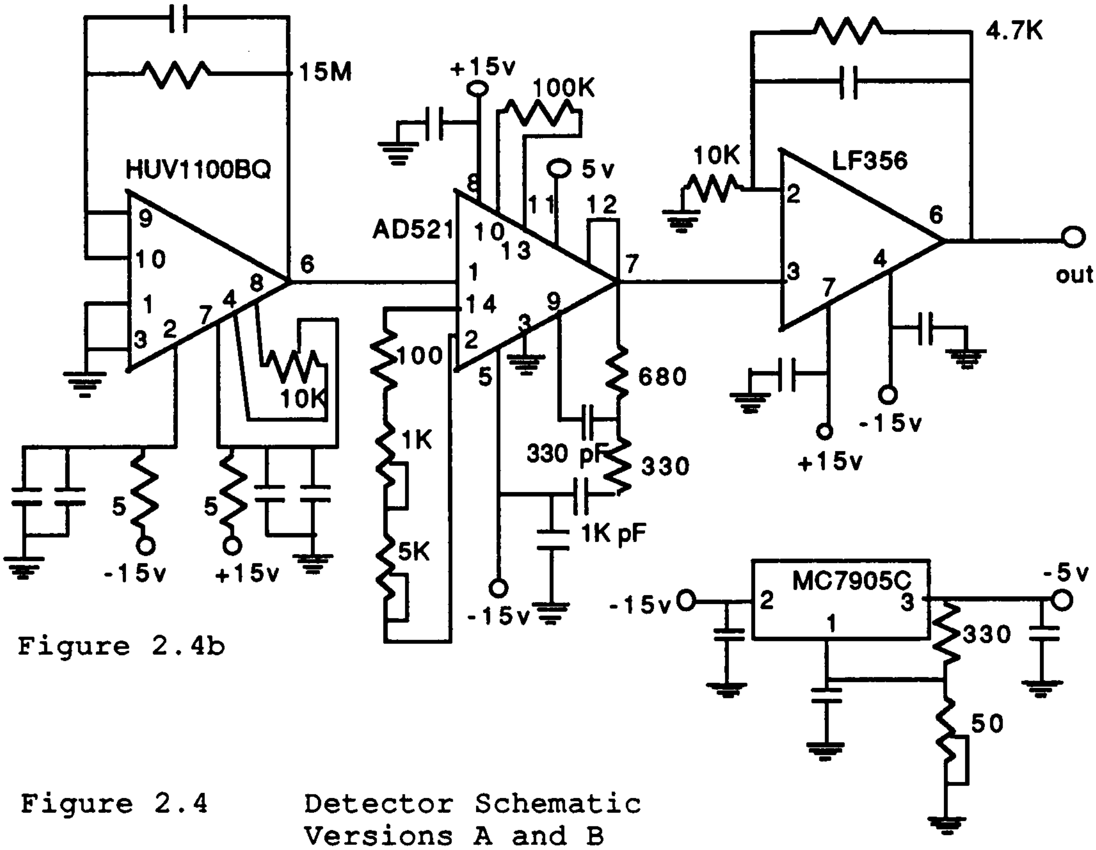

Figure 2.4b

Figure 2.4 Detector Schematic
Versions A and B

a popular isolation amplifier. The LF356 is in the inverting mode with an RC combination forming the feedback loop, whose output line is directed to the instrument's output terminals. With the exception of the additional amplifier stage on version B and some additional filtering, the two circuits are theoretically identical.

Recalling that only one detector circuit is needed for electro-mechanically separated signals, and two are necessary for optical-spacially separated signals, the same board may be used for either application. The only difference is that in the case of the former, one of the circuits is not active.

The most serious problem with the photodiode detectors is the relatively high maintenance they require. Most repairs are demanded by the trim potentiometer section of the board. Due to the method and frequency of calibration, the potentiometers are adjusted mercilessly often, resulting in a short lifetime of the trimpots and the circuit board runs that connect to them. A layout in which the pots are on their own board whose male card edge connector slides into a female connector on the board where the rest of the circuits reside would go a great length to relieving the problem. That way, if the pot board was too badly damaged from wear, it alone could be replaced. Repair would be simplified as well, as only the pot board would need be removed for most repairs. A second preventive possibility is that once the gains and offset are brought roughly into range (so the output is, say, within a volt of calibration) the fine calibration could be done by software. The idea of software-assisted calibration will be discussed in more detail later.

The second most serious dilemma is that of radio interference and noise susceptibility. The first MLR detectors contained several wire jumpers. Where the signal lines were concerned, these wire jumpers served as antennae for radio waves which abound in the test area. The later revisions (A and B) discarded the jumpers in favor of printed circuit board (PCB) implementations, greatly reducing radio interference with the signal. Still, because proper PCB connectors for photodiodes are unavailable, the leads from the photodiode to the PCB remained approximately 3.8 cm long, long enough to present a problem. A ground plane on the solder side of the PCB would serve well here, too.

Signal Separation Instrument

The same type of power supply used to power the detector circuit is used to power the signal separation electronics. This instrument is used for only the signals generated by the chopped source system, so there is only one signal line introduced to the separation circuit.

A block diagram of the circuit is shown in figure 2.5. As can be seen, the signal line feeds directly into each of two LF398 sample-and-hold IC's. The trigger shown in the figure is a TTL signal generated by the chopper's controller from an LED transmitter and receiver mounted on one side of the blade in the chopper head. As the blade rotates in the head, the mirrored sides reflect the

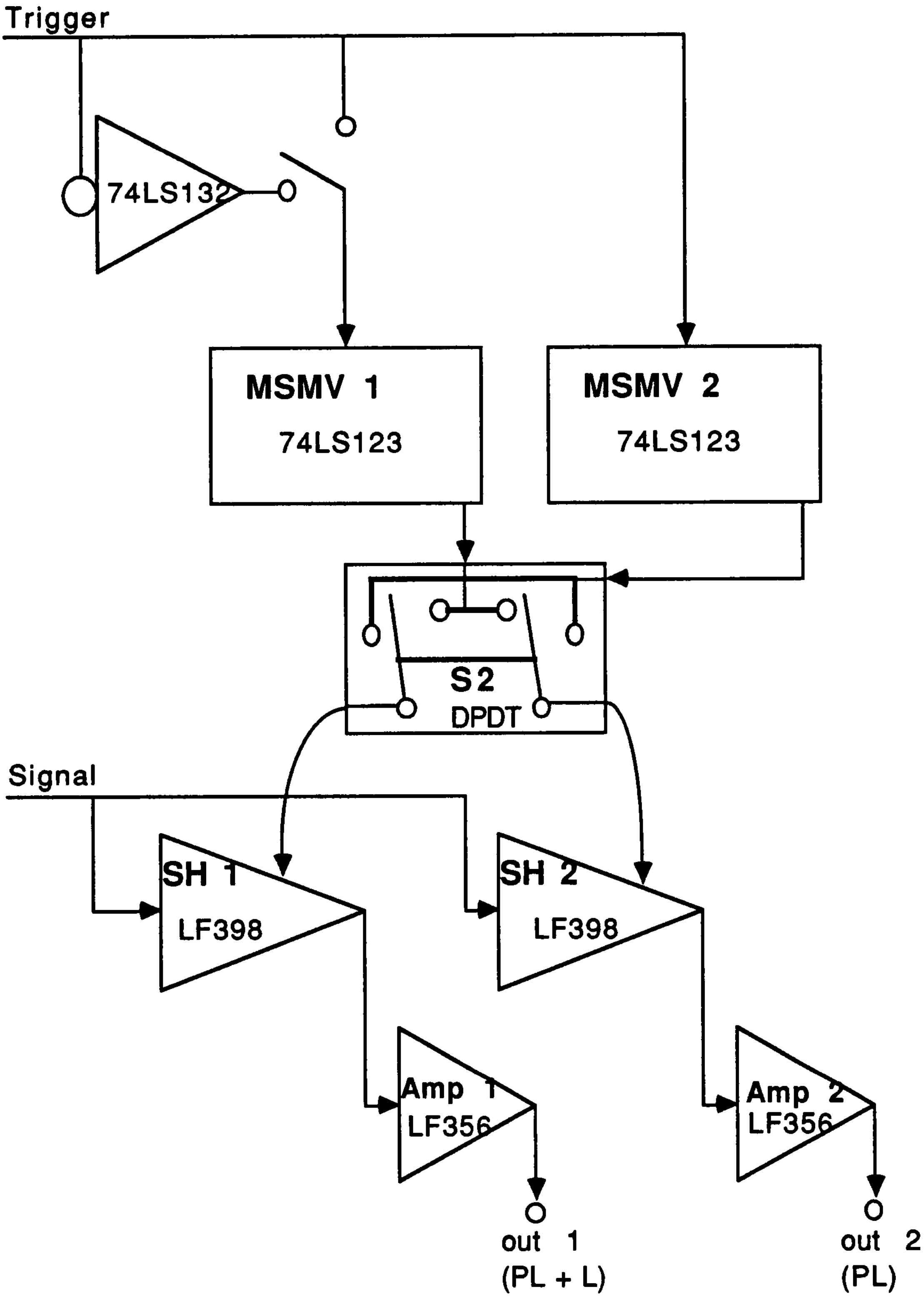

Figure 2.5 Block Diagram of Signal Separation Circuit Operation

infrared radiation from the LED transmitter into the receiver. The resulting signal is amplified and converted into the trigger signal by the controller electronics. The trigger signal serves as a trigger for each of two 74LS123 monostable multivibrators which, in turn, supply the logic signal for the sample pulse to a pair of sample-and-hold circuits. The sample-and-hold circuits sample the continuous line reversal signal during intervals selected to correspond to lamp blocked (PL) and lamp transmitted (PL + L) signals and hold the last sampled value until triggered to sample again. These sample-and-hold circuits each feed LF356 optical isolation op amps with the PL or PL + L signals, respectively. The op amps outputs are tied through terminals to the CFFF data system where the sampled signals are digitized and processed.

One can see that the double-pole, double-throw (DPDT) switch, S2, before the sample-and-hold circuits is designed to reverse the orientation of the triggers to the two LF398 sample-and-hold chips. The application for allowing trigger reversal is found in calibration of the unit. It is useful to be able to compare the calibrations of both "sides" of the circuit with the throw of a switch. The switch, S1, shown prior to the second multivibrator is a jumper used for orienting the phase of the sample period against the original signal. There are a number of capacitors which can be selected individually and a potentiometer in series used to adjust the delay and width of the multivibrator's trigger to the sample-and-hold chips. If adjustment of delay takes a potentiometer too close to its limit, the jumper S1 may be reversed to reorient the phase of the trigger 180 degrees from its last position relative to the original signal.

The block diagram in figure 2.5 is the newest version of the signal separation instrument. The new design addresses several shortcomings of the previous system, which incorporated many jumper wires and suffered from excessive corrosion. Up to four line reversal systems may use the one new instrument which is about the same size as the old version that handled only one system.

System Operation

The first step in system operation is the placement and alignment of system components. An alignment laser and mounted apertures are used to assure that the optical rails on either side of the flow train are parallel to a line running through the center of the opposing ports and to each other. After any necessary adjustments are made, the lenses and beam stops are added and aligned individually. The lamp is the next element to be brought into place, and the lamp-side lens is positioned to collimate the lamp strip element image across the flow train. If the system is a chopped-source type, a chopper head is placed between the lamp and the lamp-side lens, adjacent to the lamp. Accordingly, the detector-side lens is positioned to focus the lamp element image on the detector element, which replaces the alignment laser. A beam splitter is put into place, if one is necessary, before the lamp image is focused on the detector(s). At this time, the source lamp power supply (Hewlett Packard model 6031A DC supply) must be powered up to obtain a constant current at the level necessary to produce the desired lamp brightness temperature. Next, the apertures are closed to the proper diameters to insure fully lit lamp and plasma images across the detector surface(s).

Once the system components are properly placed and aligned, the system is ready for calibration. Before calibration it is necessary for the detector circuits and other electronics to reach thermal equilibrium; otherwise, neither the reference source nor the measurements will be consistent since calibrations shift when the electronics are warming up. For the optical-spatial separation system, a simple voltmeter is adequate for adjusting the gains and offset of the signal to within .25 VDC when no plasma is present. For the electro-mechanical separation system, however, an oscilloscope is needed for calibration. With the chopper on, the signal from the detector is viewed on the scope along with the trigger as seen directly from the chopper controller. Any necessary adjustments are made on the signal separator's trigger delays and sampling widths in order for the PL and PL + L sample periods to correspond to only a appropriate portions of the signal. Finally, adjustments to the gains and offset of the detector are made to bring the measured values exactly to predetermined values, which agree with those in the system's setup file. This final step in calibration is a very tedious one for both types of systems, sometimes requiring as much as an hour to perform. Since there are no data system terminals on the test stand, an operator doing calibrations must enter the test building in order to check each channel value or involve another person and a two-way radio.

Before a test begins, the flow train refractory is preheated for 24 hours. Moderate alignment and subsequent calibration adjustments after preheat are generally necessary due to thermal expansion of the test stand. Then, the only step left is to allow the computers to take data from the detectors and to clean optical access ports as frequently required.

Data Acquisition and Handling

Figure 2.6 illustrates in a block diagram the general path of data through the CFFF digital data acquisition system. As the diagram shows, data from the detectors arrives at a Preston model MX-B 71800 amplifier. The amplifier is simply a signal driver for one of several multiplexer boards, manufactured in-house at the CFFF, which sequentially feed the analog to digital (A/D) converter with data. The A/D converter is a Preston GMAD 29SE, with a 15 bit resolution and capable of digitizing at 50 KHz. The system controller and the destination of the digitized signals is a Data General Eclipse 250 computer. The computer converts the counts given by the A/D into digital voltages which are then transformed to appropriate engineering units of temperature (k) and transmissivity. Any necessary calculations to convert flux densities to plasma temperatures and transmissivities were entered before detector calibrations, and all the digitized and calculated channels are written to memory until a 64K block of data has accumulated. When

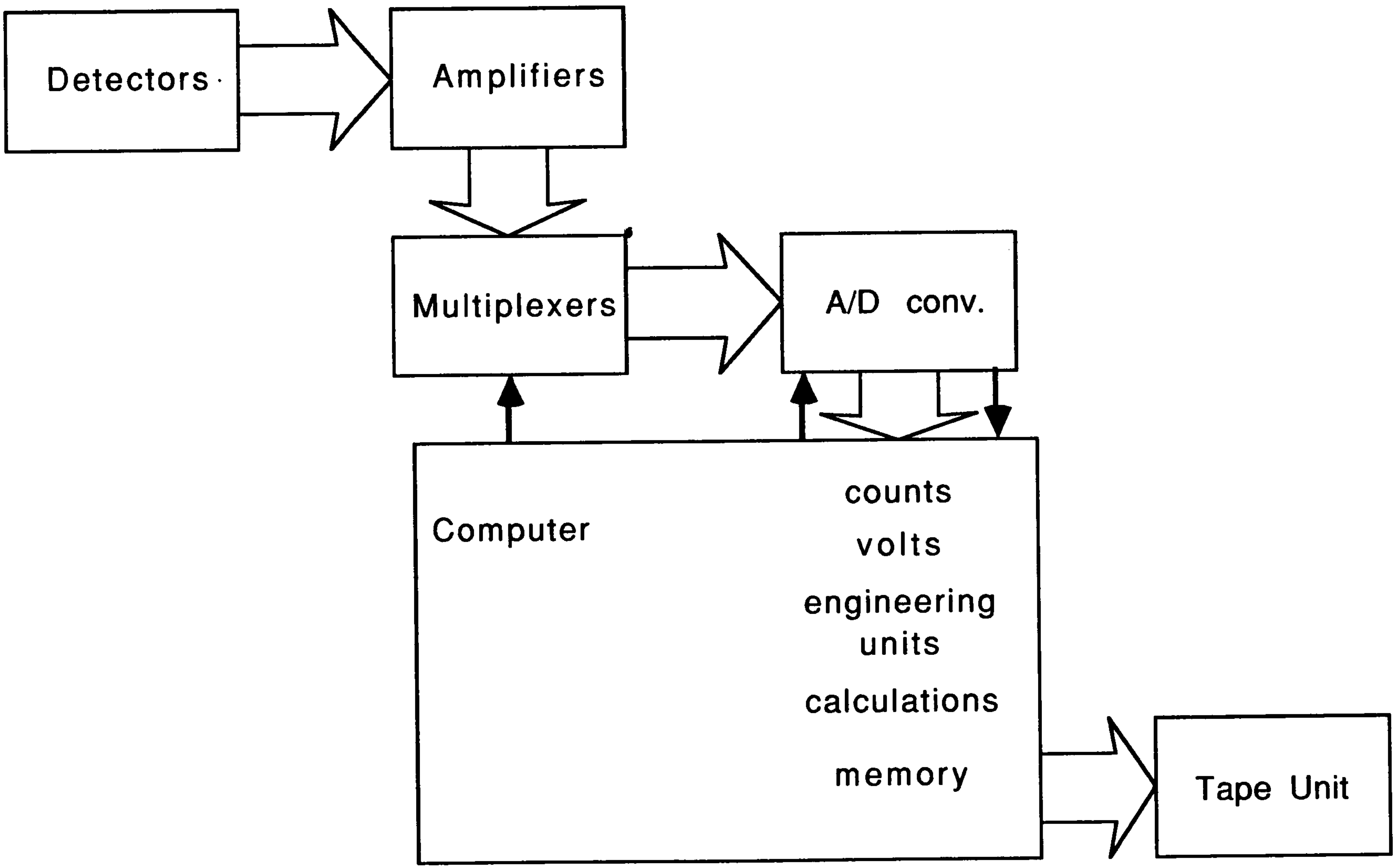

Figure 2.6 Block Diagram of CFFF Data Acquisition Data Flow Path

the required amount of memory has been filled, the block is archived to a nine-channel Kennedy 9100 magnetic tape unit.

During a typical CFFF test, 1200 channels are sampled. There are 2400 channels altogether, including those like, line reversal temperature and transmissivity, which are calculated. It is important to note that with the demands of all the hardware support (multiplexers, A/D, monitors, and the like), and maintenance of the setup file, the 250 operates at between 85% and 90% capacity during a given test period. At this high rate of operation, the channels are sampled and displayed only once every four seconds. No more is possible. A system response time of four seconds corresponds to a frequency response, considering the Nyquist Criterion, of .125 Hz. Though the detectors are currently used only for DC measurements of temperature and not for measuring frequency components, the time between samples acquired for the two different channels must be considerably shorter than four seconds if errors in mean values are to be minimized.[3] Sampling adjacent CFFF data channels alleviates this problem; however, no meaningful temperature fluctuation measurements could be attempted with such a low frequency response. Many measured parameters, literature, and common sense suggest that there are significant transient and high frequency phenomena in a turbulent plasma flow such as at the CFFF. These transients can be investigated only if the line reversal data acquisition and analysis is handled by an alternate system. This is a primary reason for establishing a stand-alone microprocessor-based line reversal system.

Another feature which has many benefits is on-line editing of the flow of data within the data system. On-line editing is simply the ability to make changes to the flow of data within the processor while the data acquisition activities run concurrently. Editing of this type would allow users to perform diverse statistical functions on particular channels on a nearly real-time basis. Experiments could be done with various forms of averaging, fast Fourier transforms (FFTs), and other forms of signal processing, analysis or data reduction. It would also be possible to change the detection wavelength to do spectral emission/transmission scans while monitoring temperature. Of course, some functions are very complex and could demand a great amount of CPU time, not to mention time to access data, so it would be necessary to place some constraints on what kind of on-line processing was available. Provided enough computational resources were available, on-line editing would be quite advantageous. However, since the present data system is not interactive with its users, on-line editing is not possible even if the processing power were available to support it.

The same reason that prohibits on-line editing with the facility-based data acquisition system makes calibration a tedious process. Understandably, general users of the data system are not authorized to make changes to the setup file (containing channel limits, and calibration constants, coefficients, and ranges) or the files containing the formulae for calculated channels. The 'proper, predetermined' values mentioned in the System Operation section are located in these files. As stated previously, the method of calibration is to bring the detector gains and zero offset to the values placed in the setup and calculation files. It would greatly simplify calibration procedure if, instead, the gains and offset could be adjusted to within an acceptable difference from the preset values, a relatively simple operation. After that is completed, the computer could extrapolate or interpolate to reach the appropriate range. Since the amplitude of the responsivity of the photodiode at a given wavelength is directly proportional to the amplitude of the SRFD of a radiation source, both calibration and the fit of the data to the respective calibration will be linear. This allows a very simple software algorithm to complete calibration. A stand-alone system could allow its setup and calculation files to be changed automatically or by the user in order to make this 'software final calibration' possible.

A final and very important point to the current MLR system is, as was stated in chapter 1, that the system is generally immobile. It cannot be used at another facility any distance away from the CFFF because of the system's dependence upon the mainframes for calibration points, data acquisition, processing, storage and display. A stand-alone system, on the other hand, could satisfy these functions as well as being quite mobile.

<u>Summary</u>

The potassium MLR system has served its purpose well at the CFFF for many years. Notwithstanding, the system has its share of problems. Each section has its own characteristic difficulties; some problems, like slag, are intrinsic to the environment or to the systems themselves and such problems may be only minimized at best, while others may find a complete solution in an improved system design or additional equipment.

Even so, it can be seen through a survey of the complete system that the performance of the MLR system is inhibited by inconvenient circuit and instrument layout, low frequency response, difficulty in including additional MLR detectors, no mobility to other facilities away from the CFFF, and a severe limitation to on-line data analysis and reduction capabilities. Since most of these problems are related to the data system, a separate computer for MLR is a reasonable solution. There are microcomputers available with ADC boards which can sample up to 100,000 samples/sec, and minicomputers available that can sample up to 1M samples/sec, not to mention the computing power to tailor on-line data analysis and signal processing tools. Though there are several issues for improvement in the entire MLR system, the way to improve it the most is to replace or amend the current ties to the CFFF data system with a dedicated processor. The remainder of the thesis will involve the development and implementation of just such a practical computer system capable of helping the MLR system to become stand-alone, thereby overcoming many of its current pitfalls.

CHAPTER 3 -- DATA SYSTEM DESIGN ISSUES

At this point there is a justification for considering a dedicated processor to support a stand-alone MLR system. Though the design is from 'the ground up', it does not preclude the consideration of commercially available systems.

The first step of a good design is the development of a definitive problem statement or list of system requirements. The following discussion outlines a compendium of criteria for performance, economic and other requirements of the system.

Performance Criteria

First of all, an MHD plasma is heavily seeded with an alkali metal, such as potassium or cesium, to promote plasma conductivity. Potassium, or the generally present sodium, emit strong, near visible spectral lines for an otherwise nearly transparent gas. MLR uses the emission spectra of these alkali ions in the plasma. Consequently, the wavelengths of interest are those between approximately 200 to 900 nm since the spectra from these metals lie in that region, specifically the doublets of sodium at 589.0/589.6 nm and potassium at 766.5/769.9 nm.

Sampling rate is a more elusive quantity. Work done at Hokkaido University in Sapporo, Japan suggests that at their MHD facility there are significant frequency peaks that exist in plasma temperature in the generator's electrode boundary layer at a number of frequencies between 3 and 35 KHz and possibly up to several MHz.[9]

For the foreseeable future, very high frequency (over 100 KHz) MLR sampling is of questionable value at the DOE CFFF. The reason is that the immediate use for very high frequency sampling would be as an indication of generator performance when combined with measures of plasma conductivity or current, but there is no generator at the CFFF site at the present time. The Japanese research, however, is still significant to plasma studies at the CFFF because there are at least two other major phenomena that have a relationship with peak plasma temperature frequencies: turbulence in the flow train and combustion stability. In past studies of plasma temperature fluctuations, due to the size of the flow train ducting and the inlet velocities, the frequency spectra trailed off at about 10 KHz.[7] This indicates the minimum frequency threshold for the stand-alone MLR system requires a 20 KHz sampling rate, per the Nyquist Criterion. While there are no plans to include a generator in the near future the efforts in Sapporo intimate that there may yet be a reason to support high frequency acquisition. Thus, it is wise to maintain as much flexibility as possible. Provided the cost is reasonable, if needs of very high frequency data arise at the CFFF or another location, the ideal system should be prepared to accommodate those needs. As a point of reference, should the unlikely need arise for a sample rate in excess of 100 KHz there is a Masscomp model 5400 minicomputer with a maximum sample rate of 1 MHz, available on a limited basis for MLR measurements.

Mobility is another driving feature. This is quite an ambiguous quality. There is little more required here than simply more mobility than the facility mainframe allows. At this point, there are no specific space requirements (i.e. the system need not be mountable in a standard 19" rack).

The final and most important performance criteria is, "How much computational and hardware power should the system possess?". First of all, the system must support data acquisition functions for two to four MLR detectors. Two of the maximum four will be of the optical-spatial type, and two will be of the electro-mechanical variety. As per their description in chapter 2, the optical-spacial detectors will require two analog input lines each. The electro-mechanical ones will require one line each if the signal separation is not performed prior to data acquisition or two each if signal separation is done before the data is acquired. The signals acquired from the detectors need not be truly continuous. That is, several seconds of high frequency data could be taken and processed, then acquired again and processed, and so on, provided the processing time is not exceedingly long (less than a few seconds). In other words, semi-continuous acquisition is continuous for the time the data is taken, but there is a gap during processing. This method is acceptable for high frequency analysis and allows reduced data instead of raw data to be stored, for example, and thus saves on space which can be a critical commodity with the large amounts of data generated in high frequency data acquisition. For DC measurements or very low frequency data, truly continuous acquisition measurements or very low frequency data, truly continuous acquisition is most attractive since a minimum of processing is necessary and storage space is not as critical.

Data storage capacity is also a necessary specification to make. If it is assumed that 32-bit data samples are calculated from the data generated by each of the four system detectors, where each data point consists of two numbers, a temperature and a transmissivity measurement, each record is 32 bytes long (1 byte equals 8 bits). Table 3.1 shows the storage requirements of three different sampling schemes. The first is a typical sampling rate for DC measurements for temperature and transmissivity only. The second, 1 KHz, is the maximum frequency resolution of the chopper-type detector since that is the maximum speed of the chopper. The third is based upon 20 KHz sampling and a 3 second processing time. Three seconds is a time period that allows a 1000 point FFT to be calculated. The columnar headings denote commonly available hard disk media.

Table 3.1 Sampling Scheme Memory Requirements

Mode	Sample Rate	MB/unit time	Storage		
			40 MB	80 MB	120 MB
Truly Cont.	1 Hz	2.64 MB/day	15.2 days	30.4 days	45.6 days
Truly Cont.	1 KHz	17.58 MB/day	2.3 days	4.6 days	6.9 days
Semi-Cont.	20 KHz	3.66 MB/hour	10.9 hours	21.8 hours	32.7 hours

Although the table shows values for it, the semi-continuous mode would be run for at most only a few hours at a time, never for 10 or more. The truly continuous examples would possibly be run for an entire test lasting up to 14 days. In all likelihood, a 40 MB hard disk drive is the minimum requirement for mass storage while the optimum, of course, would be a 120 MB unit. For multiple channel, long duration uses the Masscomp 5400 mentioned previously also has a tape unit for data backup and access to a 28 channel Honeywell Model 101 magnetic tape recorder/reproducer used for wideband data acquisition.

Computationally, the system must use the standard MLR equation[10] to convert the acquired voltages to temperatures and transmissivities of the plasma under study, display the data, and store it. Also included in the requirements is the ability to do some nearly real-time data reduction and analysis. Examples are given in chapter 2 of some statistical and frequency processing experiments that are of interest. In order to run the experiments more conveniently, on-line editing (the ability to perform data acquisition processes in the background while interactively conducting analyses of interest) would be extremely useful. The ability to run a process in the background of others does not necessarily imply a capability in parallel processing or true multitasking. A time-sharing arrangement would be acceptable if it allowed semi-continuous acquisition at the minimum frequency of 20 KHz.

Economic Criterion

Of all the criteria, cost is the most concrete. Economics has as great a bearing on a design solution as the engineering of it. If any idea is to be developed beyond an academic exercise, the economics must be considered. The fiscal year 88-89 budget line item for the development of a stand-alone MLR system is approximately

$15,000. From this amount must come a dedicated processor and its associated hardware and software. Any renovation of the detectors or signal separation electronics and any additional optical components for fiscal year 88-89 have another source of funding.

Other

A miscellaneous requirement for the system is to possess an IEEE-488 standard interface bus (often referred to as a GPIB or HPIB bus) or the provision for the addition of one. This is necessary because the Hewlett Packard power supplies used for the power to the source lamps are programmable over the standard bus. An IEEE-488 bus is not a strict requirement. The system can run without it. However, there are conditions (i.e. loss of power on the test stand) under which no entrance to the test stand is allowed. A remotely-programmable supply would be useful because the power-up state on the supplies is power off, leaving them disabled after a power interruption. At other times the interface would merely be a convenience, making for fewer necessary trips out to the instrument optics.

System Block Diagram

Figure 3.1 is a diagram of the dedicated data system's layout. The figure illustrates conceptually the major components of the system. Note that though the sections are shown as separate units they may not be so in reality. The system could be completely integrated or comprised of separate units. On the figure, the

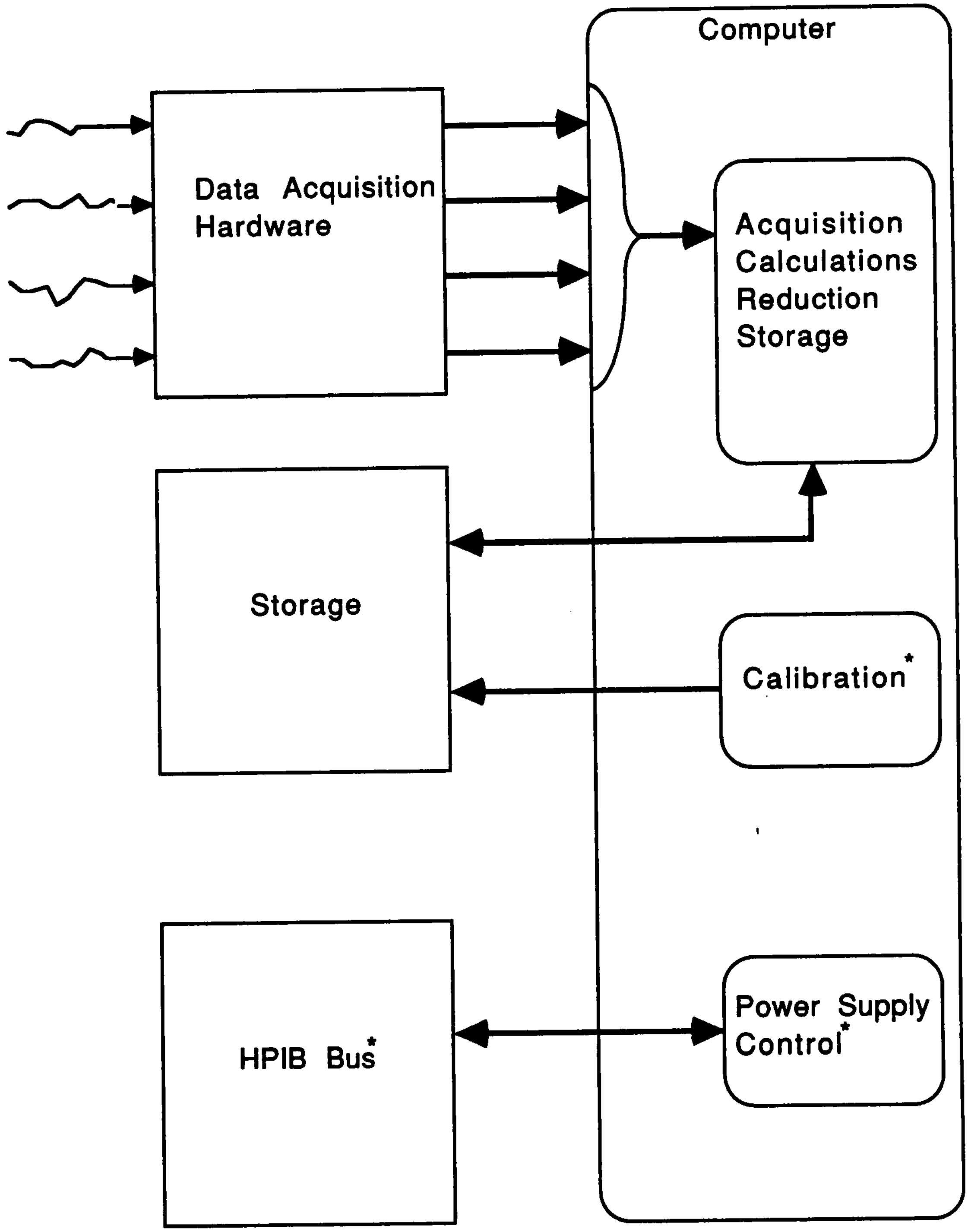

Figure 3.1 Block Diagram of Proposed MLR Processing System

program elements marked by an asterisk are those that are to operate nearly concurrently. By including the nonessential elements (i.e. software calibration, power supply control, and the IEEE-488 bus) the diagram represents the optimum case.

Further System Definition

At this point it is necessary to narrow the description of the system in order to consider specific components. The method of further defining the system is rather arbitrary. In this case the best place to begin is with the processor itself. Two questions are pertinent now. First, shall the processor be special purpose or general? Second, should the system be a commercial one or built in-house?

In answer to the first question, either a special or general purpose system will be acceptable, but a general purpose one is a better choice. Often in unique environments, a special purpose system would contain application-specific circuits and software that perform far better and faster than their nearest general purpose equivalent. In the case of the MLR stand-alone system, though, the specifications for data acquisition and handling are within those of some commercially available general purpose systems. In addition, the statistical and frequency analysis and interactive data management that are currently of interest lend themselves to a general purpose programming environment more than a hardware intensive alternative. Moreover, a general purpose system is free to grow and include more diverse solutions to problems as they arise in time. A special purpose environment generally will not have this capability.

In regards to the second question, again, either choice is valid, but there is clearly one that is better. Two factors influence the choice: design/fabrication time and maintainability. The system described to this point is not extremely complex; however, a good design and fabrication process would still be very long and expensive when the necessary skilled labor and technical resources for the project are included in the total cost. Maintainability is a large factor as well. An in-house system has the disadvantage of having to rely on internal experts for the day to day maintenance and product support that commercial products often enjoy with a simple telephone call. In-house instrumentation is sometimes the best or only alternative, but not always very economical. In this particular case, the extra effort would be difficult to justify because of the existence of commercially available systems that possess most or all of the qualifications mentioned thus far at a far lower price than the potential cost of developing a proprietary design.

So far, the description of our system is a general purpose, commercially available computer. Individual components now need to be considered based upon the performance specifications.

<u>Which Computer System?</u>

Because of the budget limit, at the present time there are basically two computers to choose from: an IBM PC or clone or a model of the Apple Macintosh. An IBM or IBM clone 20 MHz, 80386 machine will cost in the neighborhood of $3100 which includes 1 MB of RAM, keyboard, 1.2 MB floppy disk drive and controller, high resolution monochrome monitor and driver, and a 40 MB hard drive. The same machine with an 80 MB hard drive is around $3800. An Apple Macintosh II A/UX system (A/UX is Apple's version of the UNIX operating system) is available for $6240. This price includes a Macintosh II with A/UX, keyboard, high resolution RGB monitor and stand, an 8-bit video card (monitor driver), 4 MB of RAM, a paged memory management unit (PMMU), and an 80 MB hard disk drive. Incidentally, the Macintosh uses a 68020 microprocessor with a 68881 coprocessor. When the 68882 becomes available, Motorola will supply one to replace the 68881 because the DOE CFFF is affiliated with a university.

Besides a huge software base, the PC has the advantage of being $2000 to $3000 less than the Mac. The PC has a major disadvantage in the limited 640 KB of RAM the operating system can address where the Mac architecture allows up to 8 MB of RAM. This disadvantage would severly restrict the MLR system capability. Of course, there are memory expansion cards available for the PC, but with the current DOS the cards serve only as RAM disks. Moreover, the Mac operating system has the advantage of being compatible with the UNIX operating system of the CFFF Masscomp mentioned earlier.

After consideration of price, performance and the availability of third party hardware and software, the Macintosh II A/UX computer was selected. Besides RAM, a significant driving force was the availability of a graphical programming language, LabVIEW, for data acquisition, signal processing and conditioning. The interface, as the description indicates, is a graphical one. Using graphical units, data acquisition functions and manipulations can be programmed with a minimum of difficulty. Although specific hardware is not necessary, the language supplies a large functions and control library for the convenient interfacing to a variety of plug-in circuit boards manufactured by the same company. Several cards and components were chosen allowing the composite system to meet the specifications discussed earlier. Incidentally, excluding the computer, the hardware and software package were purchased for less than $6,000. The complete system hardware is outlined in the next chapter.

CHAPTER 4 -- DATA SYSTEM HARDWARE ENVIRONMENT

The hardware environment of the new data system is made up of 4 sections. The computer is, of course, the first one. The others will be introduced in the following section, followed by a description of how each is employed in the overall system.

Data Acquisition

The data acquisition is accomplished with the National Instruments NB-MIO-16H-9 multifunction (MIO) board. The MIO board is capable of 9 μsec A/D conversions over 16 single-ended or eight differential analog input channels. Two channels of digital to analog output are also provided, as are eight lines of TTL-compatible I/O and three, 16-bit timing channels. A/D conversions are done with 12 bits, and sign extended to 16. Jumpers on the MIO board provide a hardware means of setting input mode: ground-referenced single-ended, non-referenced single-ended, and differential, as well as input polarity and range. Software programmable gains (of 1, 2, 4,or 8 times) and the sampling order of the analog input channels are also supported, as well as four timing signals: scan clock (output), external trigger, external convert (for external triggering of the ADC chip), and external gate. Upon conversion, data values are sent to a 16 word first-in-first-out (FIFO) buffer where the values are held for subsequent use.

Although the A/D performs conversions in 9 μsec, the minimum 'safe' sampling time is 10 μsec since that is the recommended settling time of the analog input lines. It should also be noted that the sampling rate is divided among the number of analog channels being sampled, so with four channels being sampled every 10 µsec (100 KHz), each channel would be sampled at effectively 25 KHz. Sampling rate is, of course, software programmable.

For tests at the CFFF using the existing detectors, the MIO board's jumpers are set such that the analog input lines form eight differential channels. The reasons are: the signal sources are a long distance (greater than 15 ft.) from the computer; the input signals are typically low level (less than 3 V); the ground on each of the detectors may not be identical, and the leads must travel through a noisy environment. Other jumpers are set such that the input polarity is bipolar and input range is 20 V.

When calibration of the MIO board is necessary, a precision, variable DC voltage source or calibrator and a voltmeter are required. Both instruments must be at least .003% accurate and have a resolution of at least 100 µV in a -10 V to +10 V range. The manuals included with the MIO board outline the calibration procedure for the analog input and output channels.

As with the sampling rate and gain, the board's configuration is also programmable. The MIO board may be configured for single- or double-buffered acquisition. This is a software exercise and will be discussed in the next chapter.

GPIB Interface and DMA

For interfacing to the reference lamps' Hewlett Packard power supplies a plug-in IEEE-488 interface card, model NB-DMA-8-G, was also purchased from National Instruments. As the model name suggests, direct memory access (DMA) is also included in the card's functions. The GPIB portion is a high-performance interface, capable of reading 1 MB per second and writing 750 KB per second. GPIB commands are transferred at 320 KB per second. Since the interface bus will be used only for control of the power supplies, a relatively slow process, the 320 KB transfer rate is actually much more than is necessary.

Although the NuBus, the interface bus standard to Apple's Macintosh, is not intrinsically capable of DMA, both the MIO and GPIB cards have a proprietary bus called RTSI. RTSI stands for Real Time System Integration and was developed by National Instruments. Using the RTSI bus and the GPIB card's DMA controller, either of the cards can make use of DMA functions between themselves and the Macintosh's memory. The system default is to assume that both the DMA card and the RTSI bus are in place. Upon boot-up their presence is checked. If the DMA and RTSI are not present, then a hardware interrupt is generated, allowing the software environment to know that DMA functions are unusable.

Storage

The last component to introduce is the storage device. A 45 MB removable cartridge hard drive was purchased from MASSMICRO Systems.

The DataPak, as it is called, uses the Macintosh SCSI (Small Computer System Interface) bus for data transfer and boasts an average access time of 25 msec. A removable cartridge is an excellent solution to the storage dilemma. Essentially, additional 45 MB drives may be acquired simply through acquiring more cartridges, which average $3.31 per MB. Practically, the 45 MB size sets an upper limit to long duration, continuous, high frequency acquisition or very long, continuous, low frequency acquisition. However, referring to table 3.1 on page 33, 45 MB still allows a larger storage media than the projected needs of the current project.

System Setup

In a testing situation, setup is relatively simple. The Hewlett Packard lamp power supplies are interfaced to the computer through a standard IEEE-488 bus cable to the NB-DMA card. The software system, described in chapter 5, includes the necessary drivers for the IEEE-488 bus.

When operating at the CFFF, connections to the analog signals from the detectors on the test stand may be made from the MIO card to a patchboard located just before the input multiplexer of the mainframe data system. If operating off-site, signal lines in a twisted pair may be connected directly.

In the interest of simplifying setup of the MLR system hardware, the signal separation instrument is bypassed, opting for signal separation in the software environment of the MLR data system. Recalling that the continuous signal detectors produce two signal lines and the separated signal detector produces only one with the two signals multiplexed, the eight differential analog input lines are arranged as shown in table 4.1. The predetermined arrangement shown there simplifies the programming by allowing the software to assume that signals observed on particular channels are from a known detector type. The software can then decide which signals are to be separated and which are not.

Table 4.1 Assignment of Virtual Channels

Differential Analog Channel	Virtual Channel	Detector	Signal Type
0	0	Detector 0	PL + L
1			PL
2	1	Detector 1	PL + L
3			PL
4	2	Detector 2	muxed
5	3	Detector 3	muxed
6	4	Detector 4	muxed
7	5	Detector 5	muxed

As the table suggests, the continuous signal detector's two voltage channels can be fed into either of the two composite analog inputs. It is up to the operator to select the proper software switch to indicate which channels are being used. The chopped MLR signal may be directly fed to any of the remaining four analog input channels. A more complete treatment of the problem of software signal separation leading to the assigning virtual channels is given in the following chapter.

CHAPTER 5 -- DATA SYSTEM SOFTWARE ENVIRONMENT

The software environment is the engine behind the stand-alone MLR system. LabVIEW is the application within which the MLR software environment was created. It is a graphical programming package which employs a proprietary language called 'G'. The impetus of LabVIEW is data acquisition, processing and control. Principles of dataflow computing form the basis for the syntax of the language, which is self documenting to a large extent due to the intuitive graphical interface. In order to gain an understanding of the rudiments of LabVIEW, it is helpful to review some basic concepts of dataflow computing.

Dataflow Concepts

Dataflow computing differs greatly from the 'traditional' von Neumann theory of computing. In dataflow theory, there is no concept of a program counter or control mechanism. Unlike a sequential approach, data moves between instructions (called nodes) and the nodes are dormant until all their inputs are available. When inputs arrive, the node may fire (execute). That is the first rule of dataflow computing. The second rule is that the routes which carry the data (known as arcs) may carry only one piece of data (token) at a time. It would be a good guess that parallel execution is intrinsic to dataflow; it is. In fact, many nodes may be prepared to fire at one time. In a dataflow architecture, all nodes prepared to fire simultaneously are assigned to a functional unit and executed.[11,12] Naturally, this is not possible in a uniprocessor machine such as the Macintosh. Though true parallel processing cannot be accomplished, LabVIEW still maintains the essence of dataflow principles. That is, the programmer need not be concerned with program sequence. The rules of dataflow take care of that. Besides the absence of parallel processing, LabVIEW deviates from pure dataflow concepts in two other ways: the application does have at least one operator which does not require all inputs before firing, and arcs in LabVIEW are allowed to buffer data. Permitting the arcs to buffer data results in the capability to build and index arrays automatically as well as ease debugging by making it possible to read their contents after program execution ends.

LabVIEW

An obvious primary advantage of LabVIEW is the graphical interface itself. Incidentally, in a dataflow architecture, dataflow program graphs are the base language just as a sequential language is a base for a von Neumann machine.[11] Functions and routines are not programmed with words but by forming block diagrams using basic building blocks or blocks that are user-created. The block diagram is the program. Once a block diagram is completed an icon may be created to represent it. The icon associated with a particular diagram can be used to represent the diagram in the formation of other block diagrams, and so on.

The block diagram is one of two parts to every routine. The second part is called the front panel or, simply, panel. The two parts together are referred to as a Virtual Instrument (VI). The panel is the most common means by which a routine performs I/O. Upon the panel there are controls and indicators of various data types which correspond to input and output points on the block diagram. If a routine's panel is on top of the desktop (is the active window on the Macintosh monitor), the controls may be used to input values to the routine. To change a value of a control, the Macintosh's mouse is used to move the screen cursor to the control, and a click of the mouse's button selects the control field. If there must be a value entered, it may be entered via the computer keyboard; otherwise, if the control is binary, a click with the mouse will toggle its value. If a routine is embedded within a block diagram, there are user-defined areas beneath the icon which represent the controls and indicators of the routine's front panel. The controls may be written to and the indicators read by wiring them to the terminals of other VI's or other controls and indicators.

LabVIEW supports five data types and four data structures, listed in table 5.1 and 5.2, for use in programming.[13] In table 5.1 the X's denote what form the data type can take. Note the numerics contains integers and reals.

Table 5.1 Data Types

Type	Control	Indicator	Arrays
Binary	X	X	X
Numeric	X	X	X
String	X	X	X
Cluster	X	X	X
Graph		X	X

Table 5.2 Data Structures

Structure	Approximate
For Loop	For Loop
Selection	If-Then
Sequence	-------
While Do	While Do

It is also noteworthy that any type(s) can be used within a cluster to form a custom data type. Table 5.2 lists the data structures within LabVIEW and their nearest counterpart in a sequential-type language. Though an approximate equivalent is shown for most of them, the temptation to assume that the equivalents have all of the same characteristics should be avoided. Table 5.2 is given for a reference only.

As mentioned in chapter 4, LabVIEW contains drivers for both the MIO board and the DMA card. In addition, many VI's are device drivers for commercial instrumentation. This is especially the case for devices which possess the IEEE-488 interface bus. The front panel can be edited to appear just like the device it is meant to control. Essentially, the program is the device (hence the term Virtual Instrument) since the hardware is totally transparent to the operator.

Overall, the accessories of the package, especially the signal processing functions available, are quite impressive. With only a few exceptions, acquisition parameters are easily programmed. Within the same software environment, one can acquire data, do calculations based upon it, store it in memory, control a wide number of external devices, perform almost any common variety of signal or array processing function, and monitor the GPIB bus.

Despite the flexibility and intuitiveness of the package, LabVIEW does have some drawbacks that hamper its convenience. Editing is encumbered by the lack of wire stretching and autorouting. If an icon is to be moved to another location on the screen, all wires must be removed before the icon can be mobile. A most pivotal point is that LabVIEW was not meant to be a general purpose programming language employing aspects of a data acquisition and control language, but vice versa (i.e. a data acquisition language employing aspects of general purpose programming). Therefore, as the upcoming discussion will point out, as the number of system variables (i.e. channels being sampled or signals needing to be separated) increase, program complexity and processing overhead increase disproportionally. The increase in complexity is mainly due to a lack of basic routines and structures which address general purpose problems such as those above.

In the section that follows, the development of the stand-alone MLR software environment will be discussed. The main aim of the environment is to grant the greatest flexibility and the most complete data management functions as possible with the tools at hand.

Program Development

Stated briefly, the main objective of the system software is to allow multiple channel data acquisition for both MLR detector types as conveniently to the operator as possible, while maintaining the flexibility of user-defined processing. A secondary objective is to facilitate software calibration or at least ease in setting the calibration values and process coefficients. Another secondary objective is to allow program control and monitoring of the GPIB bus interfacing hardware, most notably the lamp power supplies, through the Macintosh.

First of all, it is evident that the software for the MLR data system will require data acquisition from the acquisition card. To make use of the MIO board, it must first be configured with software settings for data acquisition. Two modes are allowed: burst mode and double-buffered. In burst mode, an area of memory is allocated for receipt of data from the MIO board. Double-buffered mode, however, allows a large, circular buffer to be reserved in the computer's RAM. A second, smaller buffer is reserved to access portions of the circular queue and make them available for processing within the application.

When configuration and set-up of an acquisition is complete, there are VIs available for triggering and controlling it. Burst mode acquisition is fairly straight forward. There are VIs for single and multiple channel operations. Double-buffered mode offers those choices as well as routines which force the small buffer to access the circular queue sequentially or directly. In the sequential case the data written to the circular queue is retrieved in the order it arrived. If software detects an overwrite of data before it has been accessed, an error is returned. Direct mode, on the other hand, accesses the most recent block of data only. An error exists only if the portion that the small buffer is retrieving is overwritten while the buffer is reading from the queue. Until this point, data is still in 16-bit, binary form. Routines for scaling allow binary data to be converted to voltages based upon gains preset by software. After the scaling step, converted voltages are available in the form defined by the operator for any user-defined processes.

The previous background information is sufficient to define an outline to the program. Chronologically, the outline is as follows:

1) Execute the routines responsible for controlling and monitoring the GPIB bus. The operator must set current and voltage parameters and allow the program to ramp the current to the specified value. (opt.)

2) Routines for software calibration must be executed once the reference lamps and detector circuits reach thermal equilibrium. Calibration points must be saved in a file. (opt.)

3) Data acquisition hardware must be configured for burst or double-buffered mode.

4) The MIO board must be initialized with parameters for channel numbers and associated gains, sample rate, and acquisition triggering information. Also included in this section is the reservation of required RAM.

5) Data acquisition must take place at this point of the sequence. The mode of acquisition is immaterial.

6) Any acquired data must be scaled and made available as voltages to the remainder of the program.

7) If software signal separation is used, it must take place here. There must be schemes to indicate to the program which channels must be separated and which must not be. This step must be transparent to the rest of the program in order to prevent later sections from being dependent upon it.

8) MLR calculations, averages, and/or user-defined processing must be confined to this section of the software. Display and logging of data are also members of this section.

9) Sections 5 through 8 must be executed until the looping is stopped by a control from the front panel.

10) The final section is responsible for closing files and folders that are left open by previous processes. Deconfiguring all hardware is accomplished when non-destructive termination of the acquisition section of the program is complete.

11) The GPIB control and monitor routine is used to ramp the lamp currents to zero and shut down the power supplies. (opt.)

The needs of the MLR data system are such that both the sequential and direct methods of configuration are useful. This can be easily implemented as an if-then structure within the first frame of a sequence structure, guaranteeing that one configuration VI can perform either function and it occurs only once per program execution. Since GPIB interface and software calibration are optional, they may be added to the program later, pending available space.

The second frame of the sequence structure contains the set-up routine. Since this VI may execute only once for each run of the program, and it is the last routine that must appear before a repeated acquisition, it includes any data file header information and any information retrieval necessary to run the program in the set-up section.

It follows from the chronological outline that the third frame of the sequence structure contains steps five through eight, the data acquisition, scaling and calculation sections. Note that all members of this frame must also reside within a do-while loop controlled by a binary panel control. Arranged in this fashion, the program will acquire and process data until the operator initiates termination of the program.

Finally, the last frame of the sequence structure contains the termination section for the acquisition routines. Like the termination routine, many facets of the software outline have implementations that are straight forward. As noted earlier, options for configuration and set-up are handled by simple if-then structures. Other issues of implementation are not simplistic and are discussed in the next section.

Implementation

The major issue of programming the objectives is the software separation of the appropriate signals. As the MLR formula (5.1) given later in this chapter indicates, for each calculated line reversal temperature there must be one plasma (PL) and one plasma plus lamp (PL + L) measurement. A one-to-one correlation of inputs to outputs is direct with an optical-spacial detector since both PL and PL + L are continuous signals. The correlation becomes more complex with the multiplexed data from the chopped detector. Unlike the present system, the Macintosh can digitize the entire waveform instead of sampling a small portion of it. Even so, two problems arise: how the signals on the multiplexed line will be separated into its two components and how the match between the PL and PL + L signals will be made to generate an MLR temperature. Figure 5.1a illustrates a typical, non-separated MLR signal. There are several methods of separating the signal with an equal number of justifiable statistical methods that might be used to match the separated signals prior to calculation (As explained in Chapter 1, the PL and PL + L signals are not simultaneous in the chopped system and, therefore, must be matched in order for a calculation to be performed.). The most promising method of matching the signals is to apply a weighted average of the first half of one signal to a weighted average of the second half of the previous one. For example, once AB, CD and so on were separated out of the initial waveform, they would be split again into AM, MB, CN, and ND. In the scheme a weigthed average of MB would be matched to CN. Weighted averages are attractive since there is more temporal correlation between B and C than the other points to each other. A complete study of the statistics and signal processing of the signal separation and matching methods are beyond the scope of the thesis, and will not be examined in depth.

A reasonable approach to the signal separation problem is to trigger data acquisition with an external signal. In this case the

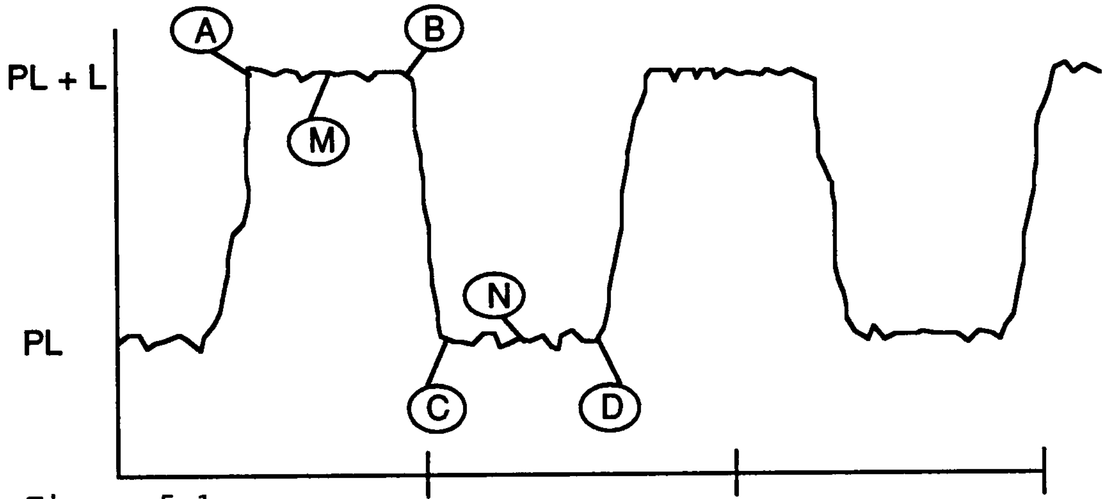

Figure 5.1a

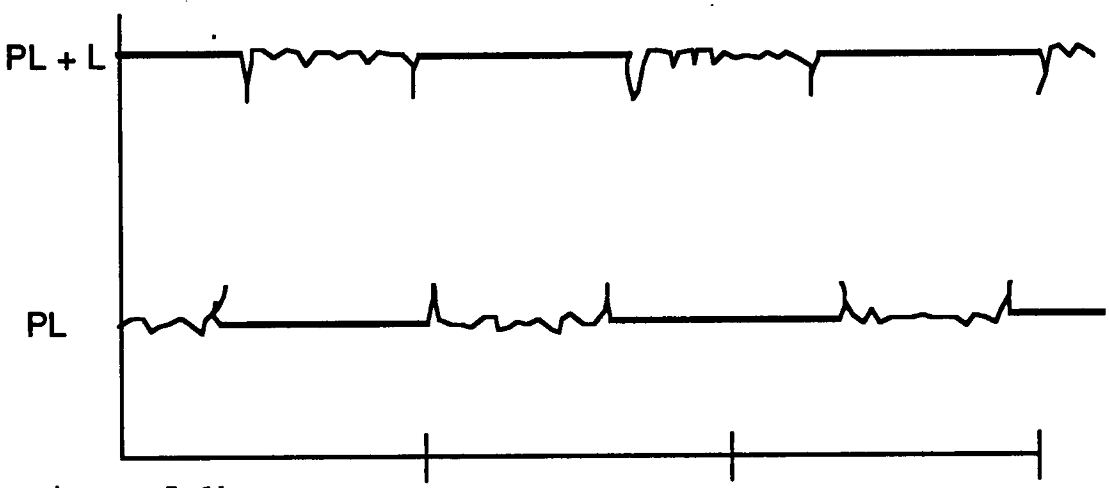

Figure 5.1b

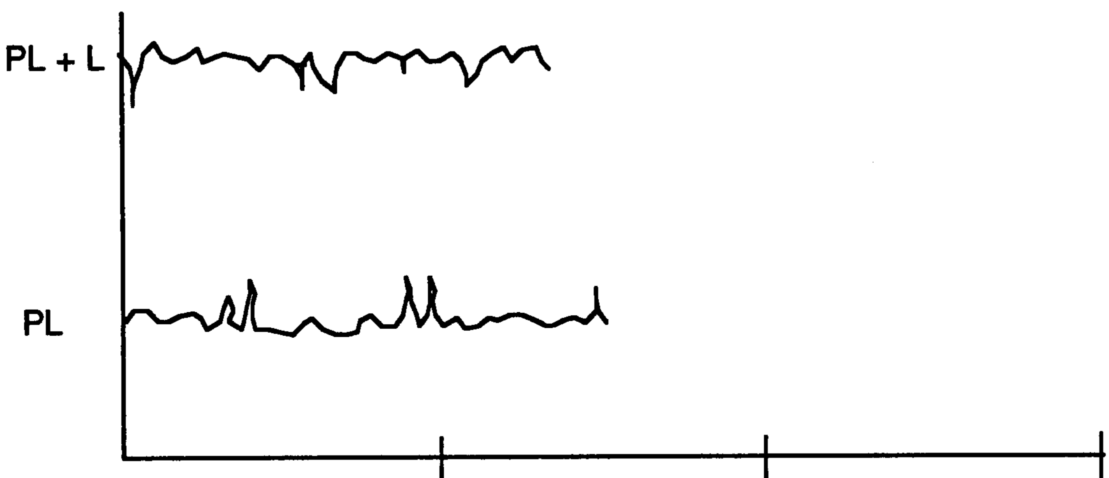

Figure 5.1c

Figure 5.1 Illustrations of Raw and Processed Waveforms trigger supplied by the chopper controller would be convenient. Unfortunately, the architecture of the MIO board makes this approach unattractive. The board does allow the input of an analog or digital trigger, but that trigger must serve as a start acquisition signal for all channels of the board. The outcome is that the optical spatial detectors are slowed to the 500 Hz frequency response that the chopped detectors are limited to. Thus, to preserve performance the data system must resort to a form of separation which is generated purely in software.

In order to show that a system is feasible that will include signal separation, the simplest forms of separation and matching were implemented. The signal separator is an on-off controller. Setpoints are specified by the operator to trigger on a high signal's negative edge and a low signal's positive one. When a high signal (PL + L) reaches a negative edge setpoint, all data afterward is considered PL. The converse is also true. After separation the signals appear as in figure 5.1b. The principles of dataflow processing dictate that all inputs for an operator are required before it can fire. In LabVIEW all data paths must be established prior to program execution. Therefore, all outputs must contain data after their operator executes; otherwise, the program would stall until all operators receive their inputs. This is the reason why there is no such thing as a null value within an array. There is always data occupying every element of a dimensioned array. Thus, the broad lines represent a default value in the two child arrays to replace data removed from the parent array. Truncation is the only way to exclude data from an array and not replace it with anything.

The broad lines between the signals show another fact of life in LabVIEW. No recursion or cyclic processes are allowed in the application. The lack of cyclic processes outlaws any form of a comparative sort necessary to translate the valid data to one end of the array which must be accomplished before truncation. For the general case when sample size and data array sizes are not constant, software separation of a multiplexed input signal is not possible with the present version of the LabVIEW software. This is a serious limitation since data array size is a function of both sample size and the number of sampled channels.

Software separation is possible for a special case in which data array size does not change. An algorithm of sorting the input data array into a fixed number of short, appended arrays is used to implement the special case. Figure 5.1c illustrates the waveform from 5.1a as it would appear after processing by the separation algorithm.

Another fundamental problem is a result of allowing channels to carry separated or multiplexed data. Early on in implementation it became evident that the overhead of permitting each channel to support either separated or non-separated data was prohibitive. Furthermore, the flexibility of allowing the user to set-up the use of each channel was of little advantage. Instead, the 8 differential analog channels are prearranged into the virtual channels of table

3.1. Yet the problem of tracking which channels are in use and how to route their data for processing still remains. LabVIEW requires that any controls or indicators which will be needed for program execution be on the front panel and wired into the block diagram prior to running. Therefore, data paths to every potential output must be intact, meaning an output path for each MLR detector and each desired calculation associated with it.

There are 3 arrays of indices and a numeric that the program maintains transparently to the user in order to track the actual and virtual channels in use during execution. All tracking information is generated by the effective VI routine. The routine calculates a numeric containing the number of virtual channels employed. Effective vector 1 is a list of the virtual channels being used, and is used by the calculation VIs to access formula coefficients and calibration values of each virtual channel as well as to send calculated data to the proper virtual channel displays. Effective vector 2 is an array containing the indices to the selection controls from the front panel. The array is used to decode the controls set by the user for function selection, storage and display modes. Front panel controls will be discussed later. The final vector is an index vector which assists the separation and matching routine to access the scaled data.

Of course, the calculation section is based primarily upon the MLR equation, shown in equation 5.1. This is of the form of the standard MLR equation for temperature calculated from measured intensities. It may be noted that the variables of this equation are detector voltages derived from the PL and PL + L signals, not intensities. The reason is because the voltages are proportional (with proportionality constant K) to the intensities incident on the detectors. Equation 5.2 is the formula for the transmission of the reference source radiation across the plasma flow. For a complete derivation of equations 5.1 and 5.2, see Winkleman.[1]

$$T = \frac{T_s}{1 - \left(\lambda \frac{T_s}{A}\right) \ln\left(K \frac{PL}{(PL) - (PL + L) + Z}\right)} \qquad (5.1)$$

$$\tau = \frac{\left| Z_L \right| - \left| (PL + L) - (PL) \right|}{Z_L} \qquad (5.2)$$

In equations 5.1 and 5.2, T is the resultant gas temperature in degrees Kelvin. Ts is the brightness temperature of the reference source, and h is the wavelength in nm of the wavelength of interest. A and K are constants of 1.439 and 1.0, respectively, and z is a calibration constant equal to the range of calibration. Z_L is the voltage read by the detector when looking at the reference lamp with only ambient air in the flow train. For reference and an example of programming in LabVIEW, figure 5.2 shows the implementation of equations 5.1 and 5.2.

Other user-selectable computations are included in the program. Averages and standard deviations are available over a sample block size, as are a real FFT and frequency spectrum. Since the latter two

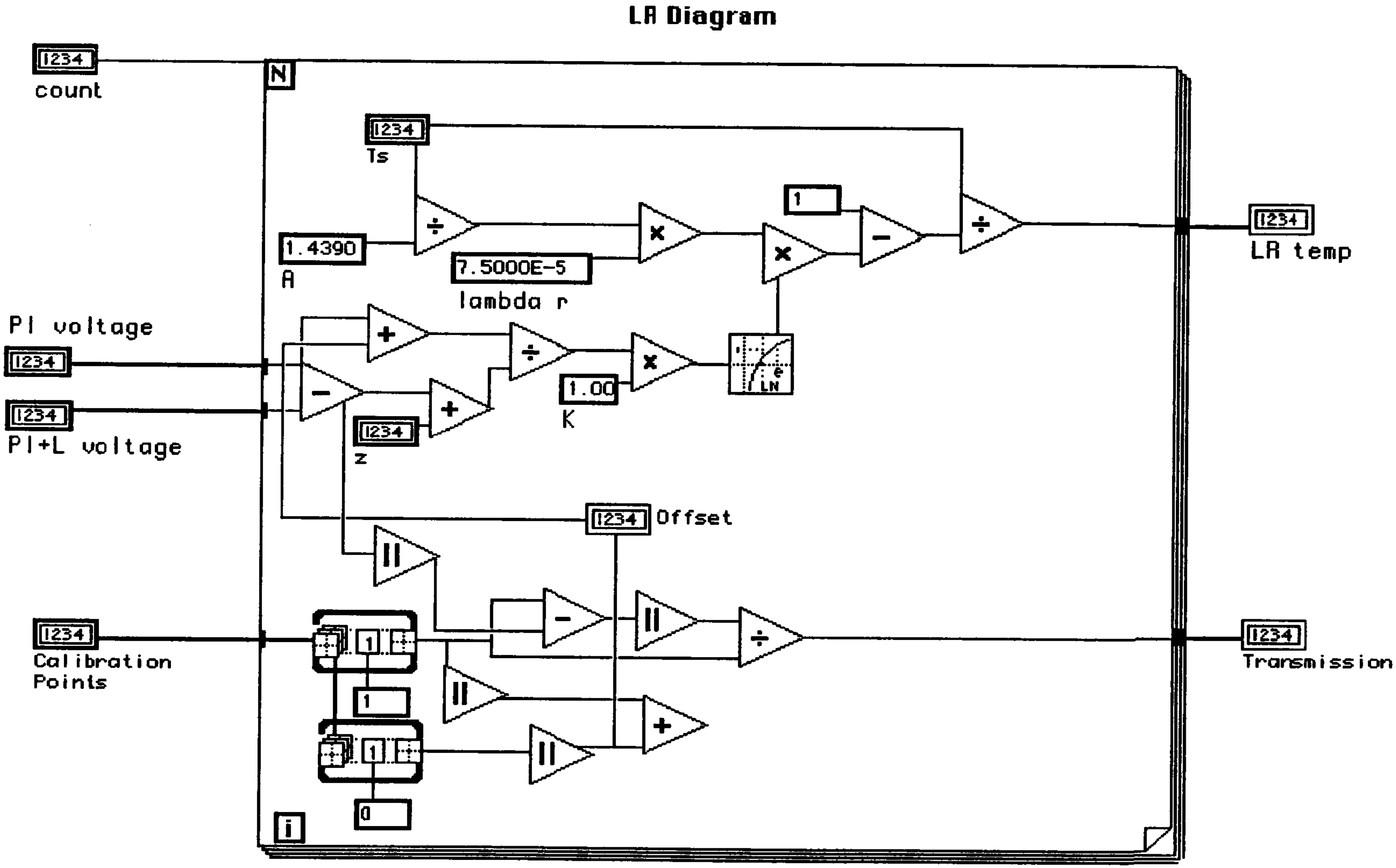

Figure 5.2 MLR Equation and Transmission Formula

functions require sample sizes of 2^n, a zero padder routine precedes them. Except for the MLR and averaging sections, the calculation functions are easily replaced with any of a large variety of available array and digital signal processing routines.

An important issue of any data system is the handling of data after calculation, namely display and storage. LabVIEW allows data to be displayed through any data type (see table 5.1) and supplies two forms of indicators used only for display: charts (a style of data type numeric) and graphs (a subset of the cluster type). It makes most sense for the MLR temperature and transmission data to be displayed with the graph data type. For large arrays, graphs are faster than charts and boast automatic scaling of the X and Y axes. Since display of any type of data takes a large amount of processing, the program contains switches such that selected calculations may be made without requiring allocation of resources to display them. The same type of selection switches are also available for the storage routines. Memory writing VIs may be enabled for the MLR temperature and transmission data as well as the average and standard deviation information. Since an operator may replace the other calculations whose information may be reconstructed from MLR data, no storage routines are available to them. For reference, figure 5.3 illustrates the formats of the header and data sections of the data file produced by the data system program.

At this point in implementation, a problem with program storage occurred. The application seemed to impose a maximum size limit of a

	Parameter	Data Type	Size
Header	Channel Vector	integer array	2 Bytes
	Gain Vector	integer array	2 Bytes
	Selection Vector	2D binary array	1 Byte
	Storage Vector	2D binary array	1 Byte
	Continuous/Burst	binary	1 Byte
	Timebase	integer	2 Bytes
	Sample Interval	integer	4 Bytes
	Circular Buffer	integer	4 Bytes
	Little Buffer	integer	4 Bytes
	Calib Points	2D real array	32 Bit FP
	Timestamp	character	8 Bytes
Data	LR Array Size	integer	4 Bytes
	LR Array	real array	4 Bytes
	Trans Array Size	integer	4 Bytes
	Trans Array	real array	4 Bytes
	LR Ave	real	4 Bytes
	LR Std Dev	real	4 Bytes
	Trans Ave	real	4 Bytes
	Trans Std Dev	real	4 Bytes
	EOF marker	----	----

Figure 5.3 MLR Data File Format

saved program at approximately 113 KB to 115 KB. After conferring with the application manufacturer, it became apparent that LabVIEW could save only 2000 objects. Actual program size depended upon what types of objects were contained. Space-saving alternatives in implementation had to be employed in order to complete the minimum objectives of the data system software. An exhaustive use of data type clustering helped the problem considerably. The most sweeping change was that displays for all channels from any one calculation step were clustered together. As noted earlier, a cluster allows a user to create a custom data type by encapsulating any type within that cluster, a practice common in PASCAL and other languages. In addition, multiple controls to the program sections were also clustered. In many cases these practices permitted one wire to replace as many as six. Obviously, there was a dramatic decrease in the number of connections between VIs, which have a maximum of 12 external connections. Fewer connections between VIs means that more routines may be consolidated into a single VI while all the individual routines' I/O paths remain intact.

The last option for conserving the object count was to remove secondary objective routines from the main program and make them programs on their own. Actually, this step has a hidden advantage. If the secondary routines become independent, their use will be purely optional. This allows their source code to be subtracted from the main program plus all controls for their execution and enabling. It will be the user's responsibility to see that if more than the main program is used, all programs will be executed in the proper order.

Clustering of front panel controls and routine I/O made the resulting block diagram much more simple and intuitive. However, the underlying dataflow was complicated by the process. Clusters are sensitive to the internal data types' positions within the cluster and to their control order. In addition, all displays located in a cluster are redrawn if even one of the displays is written to. This also provides a challenge of constructing the front panel controls in a convenient fashion for the user.

In the end product, the front panel controls consist of a cluster of eight binary switches that form the channel vector, a cluster of eight numeric slide switches making up the gain vector, a cluster of eight sets of five binary switches for the selection of calculation functions, and two clusters of eight sets of two binary switches for the selection of storage and display options for the MLR data and averages for all eight channels. It is notable that there are controls for all eight differential channels when all that is absolutely necessary is controls for the six virtual channels. Controls for all eight channels was done in order to keep the user cognizant of the origin of the signals to the MIO board.

Summary

From a set of requirements and chronological outline, a software environment was developed within the programming application LabVIEW. Methods of signal separation and matching were discussed and supporting algorithms developed. Calculation functions were presented along with the schemes for display and data storage.

Unfortunately, the resulting program is too large to show a source code listing, but is shown in figure 5.4 in a representation of the route of data through the software environment. The next chapter briefly discusses validation of the new MLR data system.

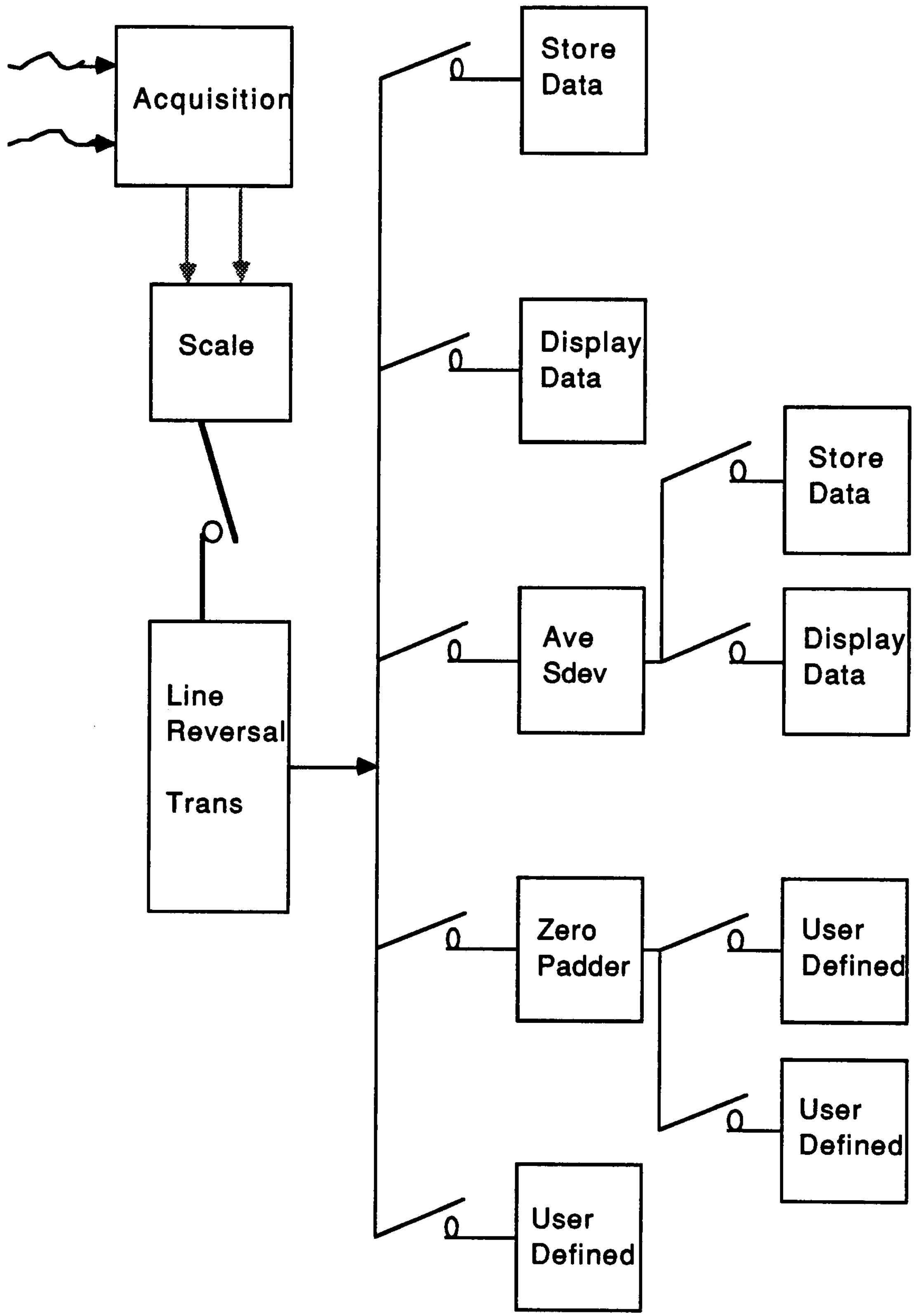

Figure 5.4 Data Route Through Software Environment

CHAPTER 6 -- DATA SYSTEM SOFTWARE VERIFICATION

During the current CFFF LMF4 tests, a model 5400 Masscomp minicomputer has been used to digitize data from several sources. MLR signals are included in the data that the Masscomp records. The data represents examples of signals typically seen during the long-duration tests of the CFFF. The Masscomp has the capability of replaying the digitized signals in analog form, thereby providing a source of actual test data with which to test the new MLR data system. The ability to play back archived data negates the need to test the improved line reversal system during an actual MHD test.

Figure 6.1 is an actual plot of temperature and transmission data calculated using data taken from a recent LMF test of the CFFF. Units of the axes are degrees Kelvin vertically, and number of samples horizontally. Units of the averages are, of course, degrees Kelvin. The plots are a result of the use of virtual channel 0, which of course is a channel reserved for separated signals. The temperatures and transmissions shown in figure 6.1 are reasonable, and the mean temperatures agree within 50°K with the bulk gas temperature calculated from combustion and heat transfer measurements. These results are a good example of typical MLR data witnessed at the CFFF.

Verification of virtual channels 4 through 6 did not function as well as the separated channels. All software components were reviewed and tested individually, and all appeared to be operating

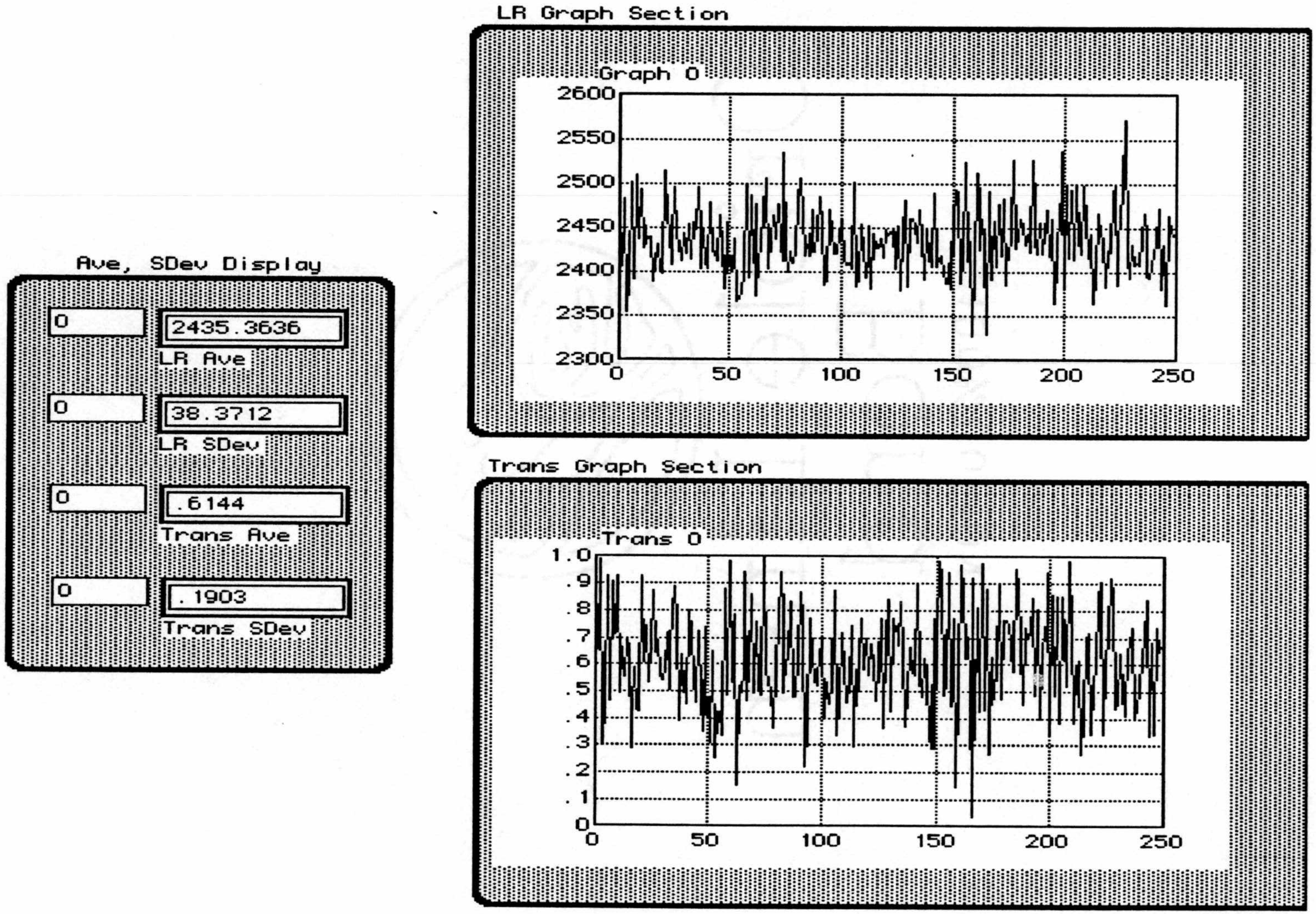

Figure 6.1 Typical MLR Temperature and Transmission Plots

correctly. However, when the individual routines were brought together one-by-one, the entire application failed as the matching portion of the signal separation routine was added. Debugging is prohibited when the application crashes because all buffers and dynamic memory locations are erased. Writing trace values to a file is a possible way to debug in this situation, but only if the exact number of inputs, data types, and order of inputs are known in advance. Instead, all pertinent values were output to the monitor. This method is acceptable since the program executed slowly enough to review the outputs before the LabVIEW application crashed. A conference with the application manufacturer revealed that under rare situations, some functions of LabVIEW fail to operate and result in a crash of the application itself. LabVIEW does not impose timeout limitations upon programs written within it. It is not possible for the program to overwrite memory vital to LabVIEW and corrupt the application, nor is it likely that the program exhausts the 5 MB of RAM available to execute it. A reasonable postulation is that the function attempted within the signal matching routine is not executable in the present version of LabVIEW.

CHAPTER 7 -- SUMMARY AND RECOMMENDATIONS

This work reviewed what MLR embodies and its use at the U.S. DOE CFFF. The scope also included the design issues necessary to consider improvements to the data processing element of the MLR system. In due course a new, microprocessor-based data system was developed and verified using prerecorded test data.

Several problems within the total MLR system were pointed out, but most of these limitations are a result of the mainframe dependence of the system. Low frequency response, lack of mobility of the system, and a lack of flexibility to include on-line data analysis and reduction capabilities are results of that dependence.

System requirements were outlined such as sampling rate, minimum computational capabilities, memory needs, and economic limits. Preliminary design questions were addressed here such as, "Buy or build?". The culmination of this evaluation was the selection of a computer on which to base the data system and the choice of the associated hardware and software environments.

The MLR system software was developed using a data flow environment and an outline of the software development was described. The major issues and pitfalls of implementation were also discussed in detail. Software separation of the PL and PL + L signals was determined to be impractical for regular operation of the existing software.

Verification of the system software was successful for separated data, but failed for multiplexed signals. Although the signal matching routine failed, it does not result in a serious future limitation. The upcoming version of the application software, LabVIEW 2.0, will permit recursion and cyclic processes, allowing much more simple and general algorithms to be developed for signal separation and pairing. Until that time, the program may be changed to accept only separated data. That way, the already existing signal separation electronics may be employed to supply separated signals to the computer's MIO board. That is not a disadvantage because the signal separation instrument is very inexpensive and has been recently refurbished. Its operation is fast and quite reliable, while relieving the computer of the overhead of tracking indices and data formats of the mixture of separated and non-separated virtual channels. Less overhead translates into faster execution and/or more processing time available for data reduction and analysis. Thus, software separation is not advised.

Yet, much more could be done to further enhance the operation and usefulness of the data system. Since software separation will most likely be possible in the near future, statistical methods may be developed to separate and pair data as accurately and correctly as possible. In addition the updated software will be executable code only, meaning that the graphics will be 'pre-compiled' and not interpreted at each program execution. Because of the pruning of the compilation step, execution is predicted to be up to 10 times faster.

With a dramatic increase in speed such as that, particulate corrections and more complex schemes of averaging could be built into the software without degrading program performance. Other program extras are possible, as well. For example, slagging alarms may easily be installed into software to alert operators when clearing of optical ports is necessary or the program may directly control a slag-clearing device. Still, the overall purpose of the project, to improve the operation of the MLR system by applying a dedicated processor, is realized in the data system developed herein.

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VITA

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