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EMI/EMP RESISTANT DATA BUS

SPECTRONICS, INC.
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RICHARDSON, TEXAS 75080

SEPTEMBER 1976

TECHNICAL REPORT AFAL-TR-76-99
FINAL REPORT FOR PERIOD OCTOBER 1973 - SEPTEMBER 1975

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AIR FORCE AVIONICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

This report has been reviewed and is approved for publication.

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FOR THE COMMANDER

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REPORT DOCUMENTATION PAGE

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data transmission	optical interconnect	bit error rate	
light emmiting diode	passive coupler	photodetector	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This document is the final report of a development program concerned with the design and fabrication of an eight station EMI/EMP resistant avionic data bus. Airborne avionics systems are moving toward the use of party line multiplex data buses for the transmission of the growing number of digital signals found in modern aircraft. Optoelectronic technology provides a data bus interface system consistent with military requirements that is potentially superior to wire techniques-particularily in the areas →

389 381

of ground loop noise immunity and EMI/EMP sensitivity. The purpose of this program is the development and fabrication of an optoelectronic data bus so that its performance can be compared directly to the performance of systems using twisted pair, coaxial cable and waveguide. The opto-electronic data bus developed on this contract uses GaAs Light Emitting Diodes (LED's), flexible Fiber Optic Bundles, Silicon PIN Photodiodes and passive optical couplers. The passive optical couplers developed on the initial phase of this program are a necessity for the realization of a true optical bus. The optical couplers are required in an optoelectronic data bus so that each station can receive optical signals from the bus and transmit optical signals onto the bus. By this means, each station on the bus can communicate with every other station. The report emphasizes the design approach and characteristics associated with the critical opto-electronic interfaces. Overall system description is also presented. The system features eight Multiplex Terminal Units (MTU) inter-connected with a nine port radial coupler. Plugable optical interfaces are employed with fiber optic cable lengths of 10 ft., 20 ft., 30 ft., and 50 ft. This provides for a maximum bus length of 100 ft. The system uses unipolar Manchester coding on the optical bus with a data rate of 10 M bit/s and a worst case bit error rate of 1×10^{-8}

1 in 100 million.

FOREWORD

This interim report describes the design, fabrication and evaluation of an EMI/EMP Resistant Data Bus by Spectronics, Incorporated; Richardson, Texas. The work was performed for the System Avionics Division, Air Force Avionics Laboratory, Wright-Patterson AFB, Ohio. The work was done on contract number F33615-74-C-1001 Project 2003-07-04. The US Air Force project engineer was Mr. David Zann of the System Technology Branch (AFAL/AAT). The program manager was J. R. Biard; the project engineer was J. E. Shaunfield. Research on this contract was conducted from October 1, 1973 to September 19, 1975.

The author wishes to acknowledge the contributions to this program made by David A. Zann, K. C. Trumble, and J. W. Bain of the Avionics Laboratory and R. S. Speer, M. R. Taylor and L. L. Stewart of Spectronics, Incorporated.

This report was submitted by the author in February 1976, has been reviewed, and is approved for publication.

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SECTION I
INTRODUCTION AND SUMMARY

This document constitutes the final technical report of a 24 month development program for the design, fabrication and demonstration of an EMI/EMP resistant avionic data bus. The data bus consists of eight terminals with each providing the basic multiplex terminal unit (MTU) function. The data bus system features plugable optical interfaces with a bit rate of 10M bit/s.

The design concept for advanced avionic systems now under development is moving toward the utilization of centralized data management techniques which emphasize automatic operation, maximum use of sensors, mission flexibility, growth capabilities and fault tolerance. This change in design concept places stringent requirements on the data distribution system which can not be met by the dedicated hard wire approach used in the past.

The principal technology related area in this research and development contract concerns the design, fabrication and evaluation of a multiterminal optical data bus which can further be broken down into three major tasks:

- design, fabrication of passive optical coupler so that construction of the optical bus can be implemented.
- design, fabrication of the optoelectronic interfaces with the constraints of the optical signals of a data bus environment.
- design, fabrication of a multiplex terminal unit to demonstrate the optical bus in a true simulation of multiplex operations.

This report describes the construction of the optical radial coupler, the design and construction requirements of the optoelectronic interfaces and the design and construction of the multiplex terminal unit.

The construction of the optical data bus was made with modified electrical connectors to provide the plugable optical interfaces. This technique demonstrates the similarities in the optical and electrical requirement, and the feasibility of providing the optical requirement with minor changes in the proven electrical connectors.

Tests performed on the optoelectronic data bus, showed the system met or exceeded all specifications called out in the subject contract. For the fiber optic cables supplied with the system, the worst case error rate for all stations is less than one error in 10^8 bits for the 10M bit/s data rate.

SECTION II
GENERAL SYSTEM DESCRIPTION

1. Introduction

The data bus system is a time division multiplex system capable of handling actual data transmission between remote terminals at a data rate of 10M bit/s. The bus configuration, as shown in figure 1 is basically as described in Reference 1. The basic equipment supplied on this contract (figure 2) is the Multiplex Terminal Unit (MTU), Control Multiplex Terminal Unit (CMTU) and the Optical Bus. The basic differences in the supplied equipment and Reference 1 are:

(1) Data on the bus is 10M bit/s optical instead of 1M bit/s electrical. To the extent practical, a complete 10:1 rate scaling was done--preamble lengths, interword delays, etc. being one tenth of the value specified in the standard. (MTU-SSIU interchange is per the standard 1M word/s).

(2) The MTUs and CMTU were constructed as stand-alone units rather than plug-in modules.

(3) The MTUs and CMTU contain the AC-to-DC power supplies required for all internal functions. (The standard specifies that DC power for an MTU is to be supplied by its respective SSIU).

All items of hardware delivered on this contract are listed in Table 1.

The data bus functions asynchronously in a command/response mode. All transactions on the bus are half-duplex operations, controlled solely by the controller through the CMTU. Information is transferred on the bus by messages comprised of three types of words:

(1) command word
(2) status word
(3) data word

The message format is shown in figure 3 where the three modes of bus operation are presented.

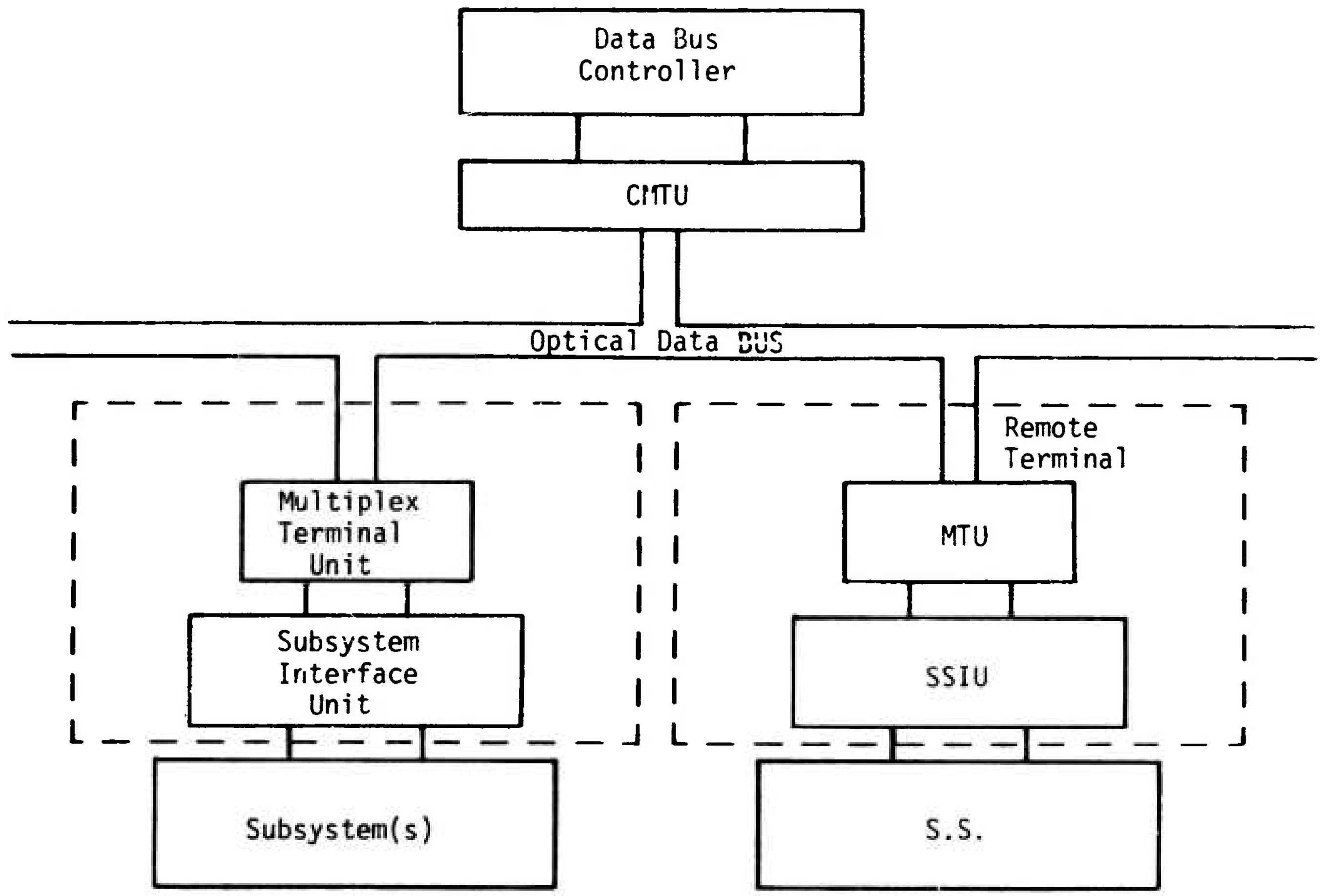


FIGURE 1 : Data Bus Configuration

TABLE 1. EQUIPMENT SUPPLIED

Multiplex Terminal Unit (MTU)	7 each
Control Multiplex Terminal Unit (CMTU)	1 each
MTU Test Set	2 each
CMTU Test Set	1 each
9 port Radial Coupler	1 each
Fiber Optics Radial Coupler Cable Assembly	1 each
Consisting of:	
2 each 10 ft. fiber optic cable	
2 each 20 ft. fiber optic cable	
2 each 30 ft. fiber optic cable	
2 each 50 ft. fiber optic cable	
SSIU/MTU interface cable	2 each
Controller/CMTU interface cable	1 each
Transit Cases	6 each
Power Outlet Strips	3 each

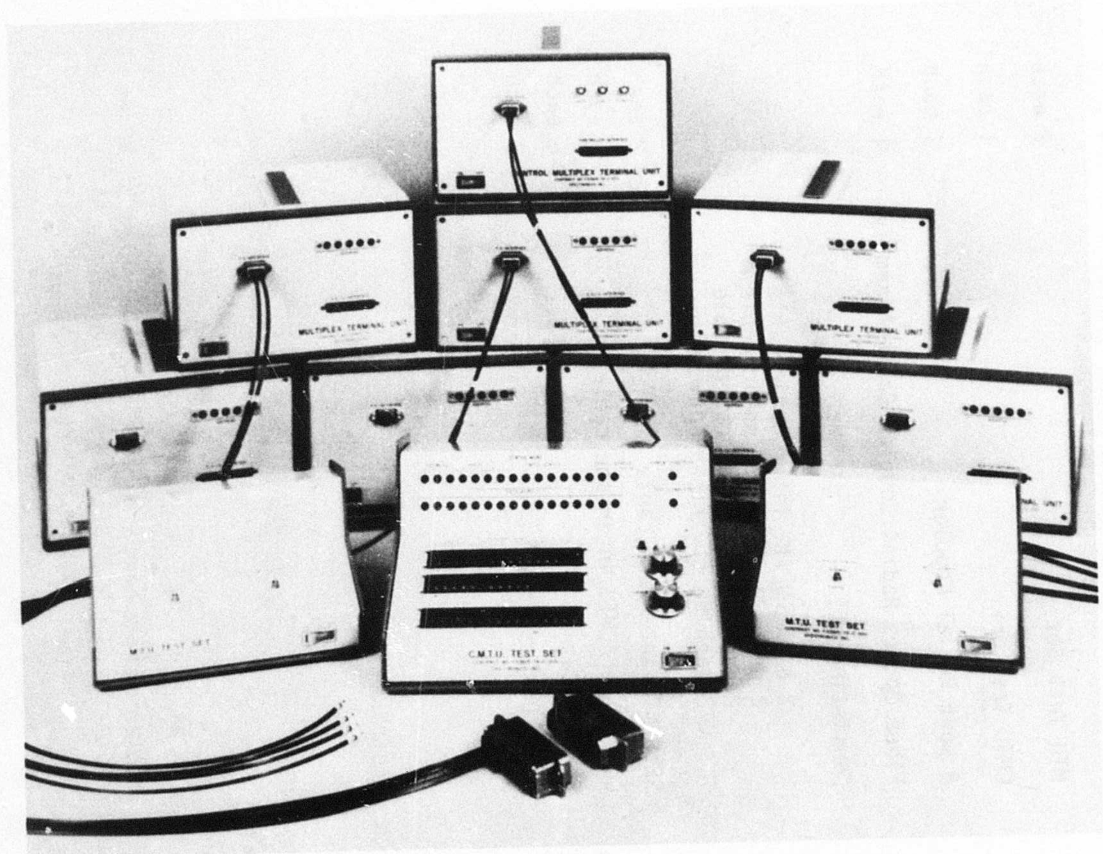


Figure 2: Data Bus Equipment

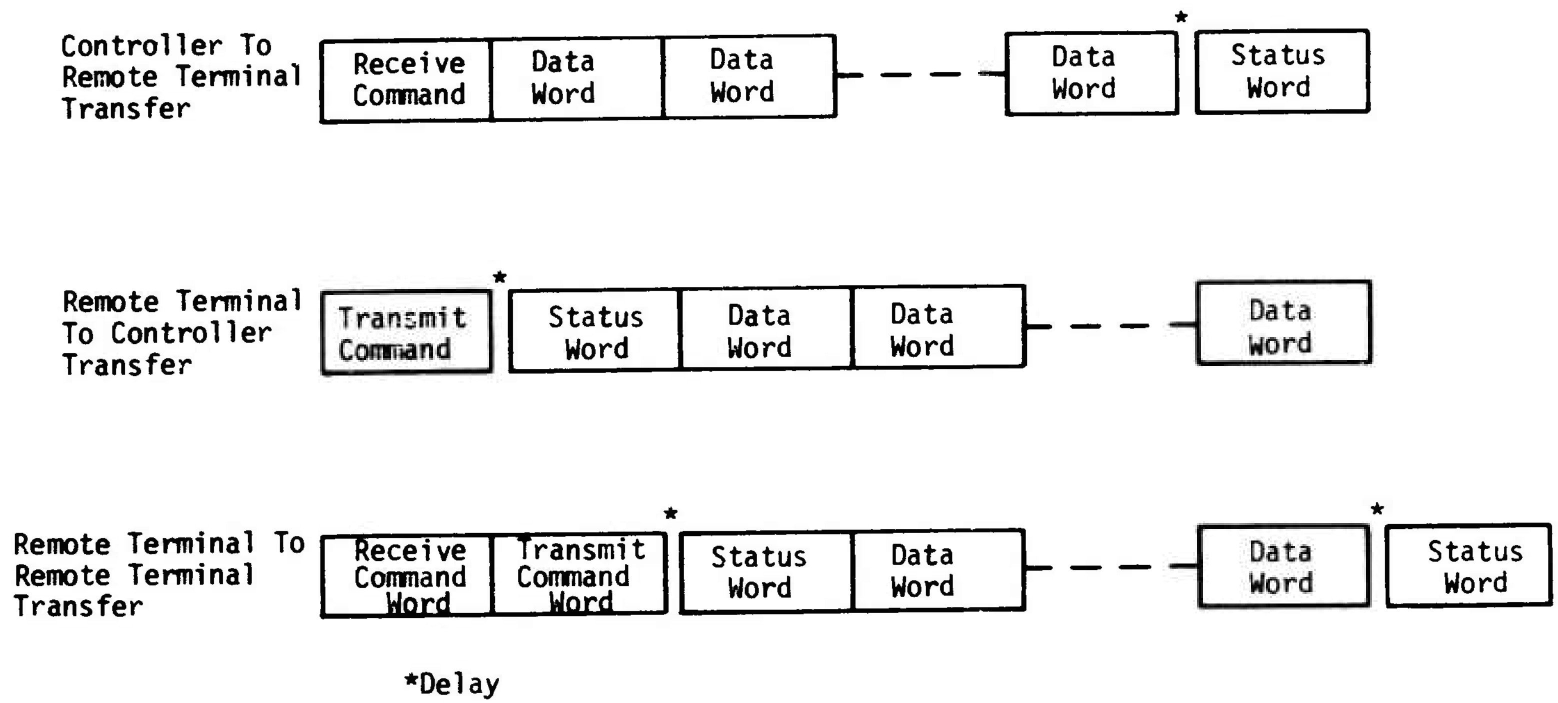


Figure 3: Message Formats

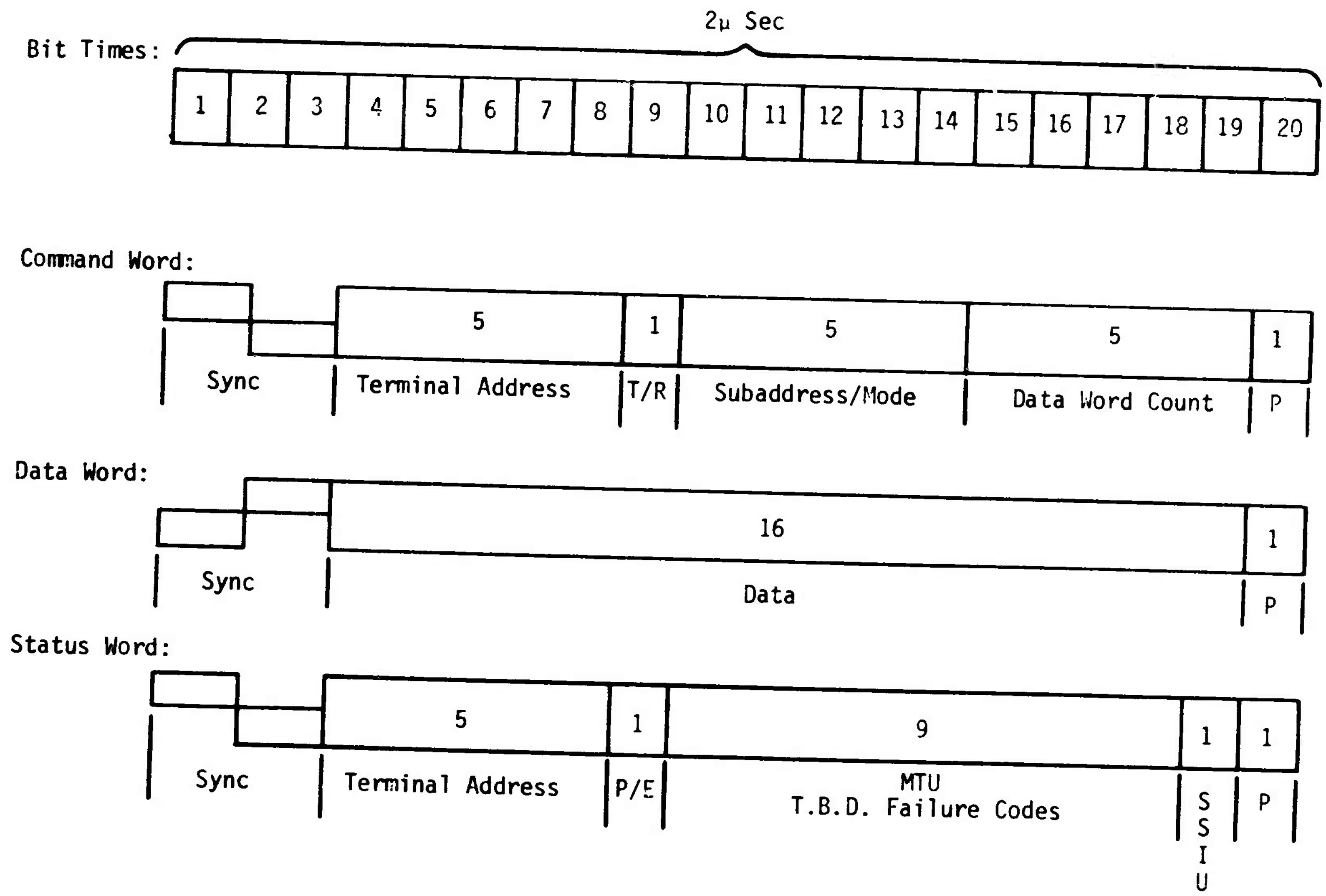


Figure 4: Word Formats

In the controller to remote terminal transfer mode, the controller will issue a receive command to the remote terminal, followed by the data words. The remote terminal will then respond to the controller with a status word.

In the remote terminal to controller transfer mode, the controller will issue a transmit command word. The remote terminal will then respond with a status word followed by the data words.

In the remote terminal to remote terminal transfer mode, the controller will issue a receive command to the receiving remote terminal followed by a transmit command to the transmitting remote terminal. The transmitting remote terminal will then respond with a status word followed by the data words. To conclude this transaction the receiving remote terminal will respond with a status word.

The command, status and data words are each twenty bit times in length including sync and parity, figure 4 shows the format of each type of word.

The command word is comprised of a three bit time sync waveform, five MTU address bits, transmit/receive bit, five SSIU code bits, five word count bits and a parity bit.

The data word is comprised of a three bit time sync waveform, a five bit MTU address, a parity error bit, nine MTU failure code bits, SSIU status bit and a parity bit.

The data code on the bus is an Optical Manchester. In this code, a logical "1" is a high state for the first half bit and a low state for the second half bit, a logical "0" is a low state for the first half bit period and a high state for the second half bit period.

There are two sync codes for the three types of message words.

Positive Sync

Negative Sync

The positive sync shown in figure 5 is used in the command and status words. It is an invalid Manchester code where the first three half bits are in the high state and the last three half bits are in the low state.

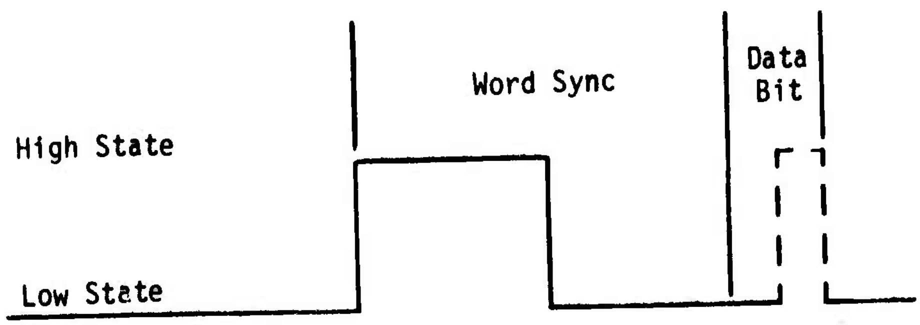


Figure 5. Command and Status Sync

The negative sync shown in figure 6 is used in the data words. It is an invalid Manchester code where the first three half bits are in the low state and the last three half bits are in the high state.

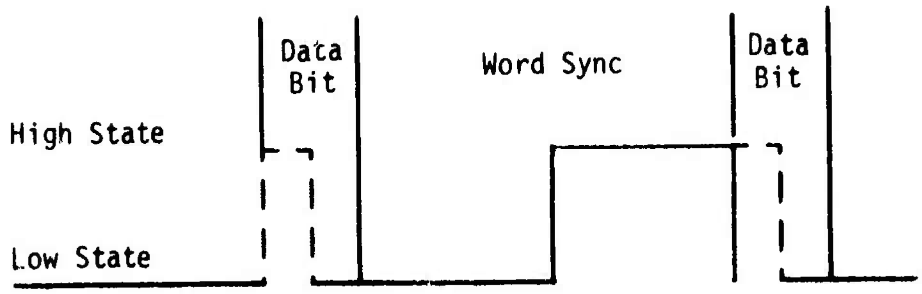


Figure 6. Data Sync

2. MTU

The Multiplex Terminal Unit provides the interface function between the optical data bus and the Subsystem Interface Unit (SSIU). The MTU responds to a bus command received from the CMTU. Data transfer from the CMTU to the MTU is held on a message basis until the last data word is properly received by the MTU, at which time the entire block of data words is transmitted to the SSIU. The MTU responds to a valid transmit or receive command within .5 to 1.5 microseconds after receipt of the last bit of the command or last data word.

The MTU provides the following functions for the remote terminal:

1. Provides a 4 MHz clock to the SSIU
2. Checks incoming command words for:
    a. correct bit count
    b. parity
    c. correct address
    d. transmit/receive command
3. Checks incoming data words for
    a. correct bit count
    b. parity
    c. data drop outs

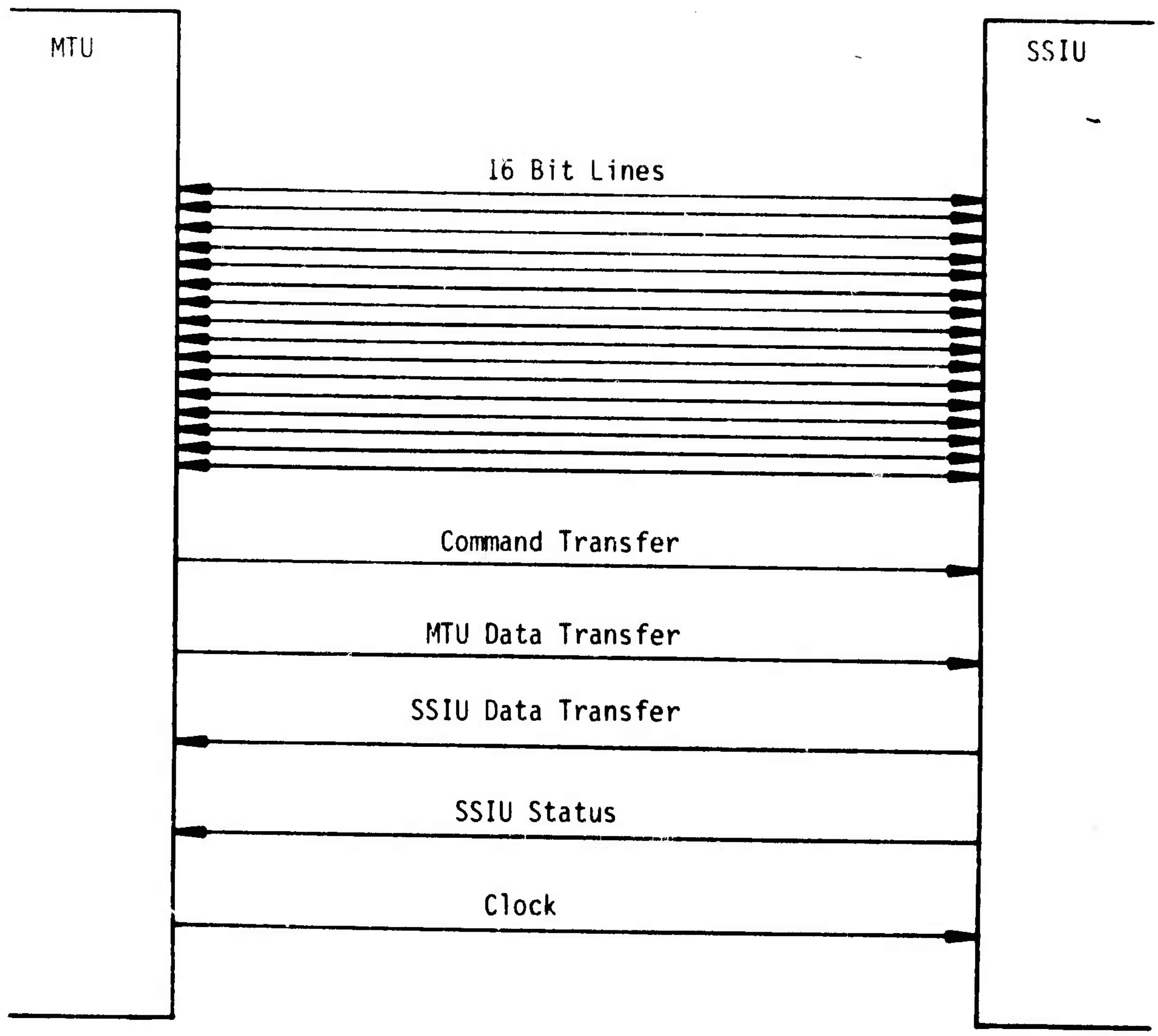


FIGURE 7: MTU/SSIU Interface

The MTU/SSIU interface consists of control, clock and bit lines as shown in figure 7 . This interface is controlled by the MTU command transfer line. Interface timing is shown in figure 8 .

The MTU designed to perform the above functions is shown in the block diagram of figure 9. The received Manchester data stream is monitored by the sync detector to detect a positive sync preamble. When a positive sync is detected the following 17 data bits are converted from the serial Manchester BI-ϕ format to a parallel NRZ format. This parallel command word is then checked for parity and correct address. If parity and address are both correct, the command word is stored in the Command Register while type of command is decoded from the T/R bit.

When the MTU receives a "transmit" command, the command word is transferred through the channel select and data transceiver to the SSIU. At the same time transmission of the MTU status word is begun, the SSIU, upon receipt of the transmit command word, will start transferring data words to the MTU. These data words are transferred through the data transceiver and channel select to the buffer memory. These data words have to be temporarily stored because data transfer between the MTU/SSIU is twice the data rate of data transfer on the optical bus. When a data word is to be transmitted it is read from memory and transferred to the output section of the MTU where parity bit is added and the word is converted from a parallel NRZ format to a serial Manchester data format with sync addition and is then transmitted.

When the MTU receives a "receive" command word, it immediately looks for a negative sync format and data word. Each data word is received and checked for parity in the same manner as the command word. It is then stored in the data register where it will then be read into memory. After the last data word is received and stored, transmission of the status word is begun. If all of the data words have been received with no errors, the receive command is then transferred through the channel select and Data Transceiver to the SSIU. The channel select is then switched to the memory and the data words are transferred to the SSIU.

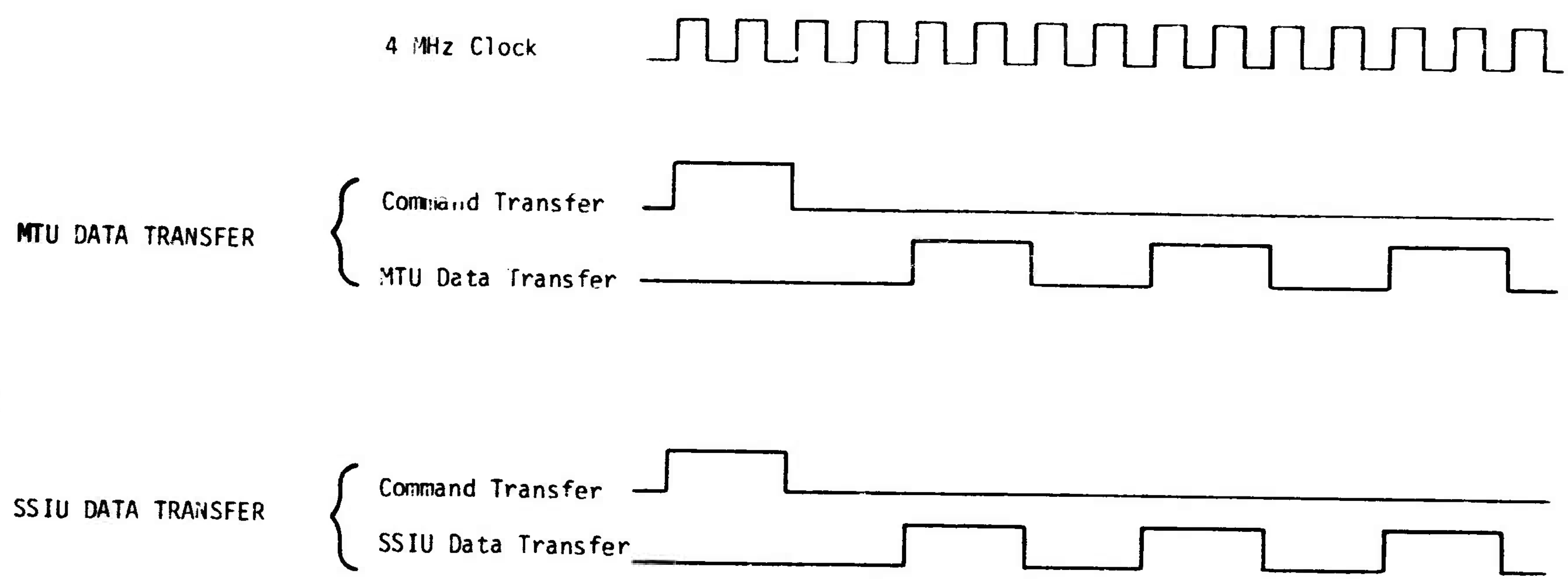


Figure 8: MTU/SSIU Interface Timing Diagram

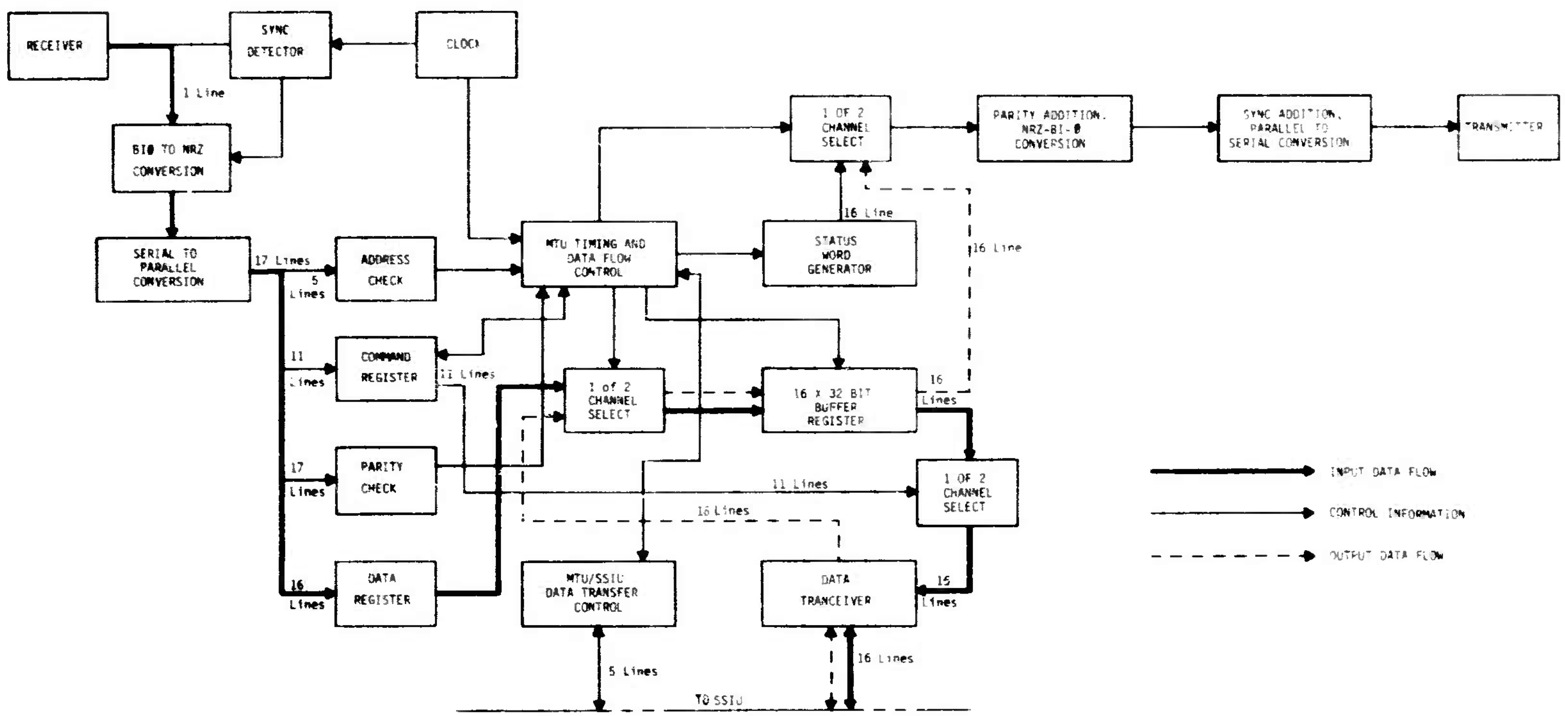


Figure 9: Data Bus MTU Block Diagram

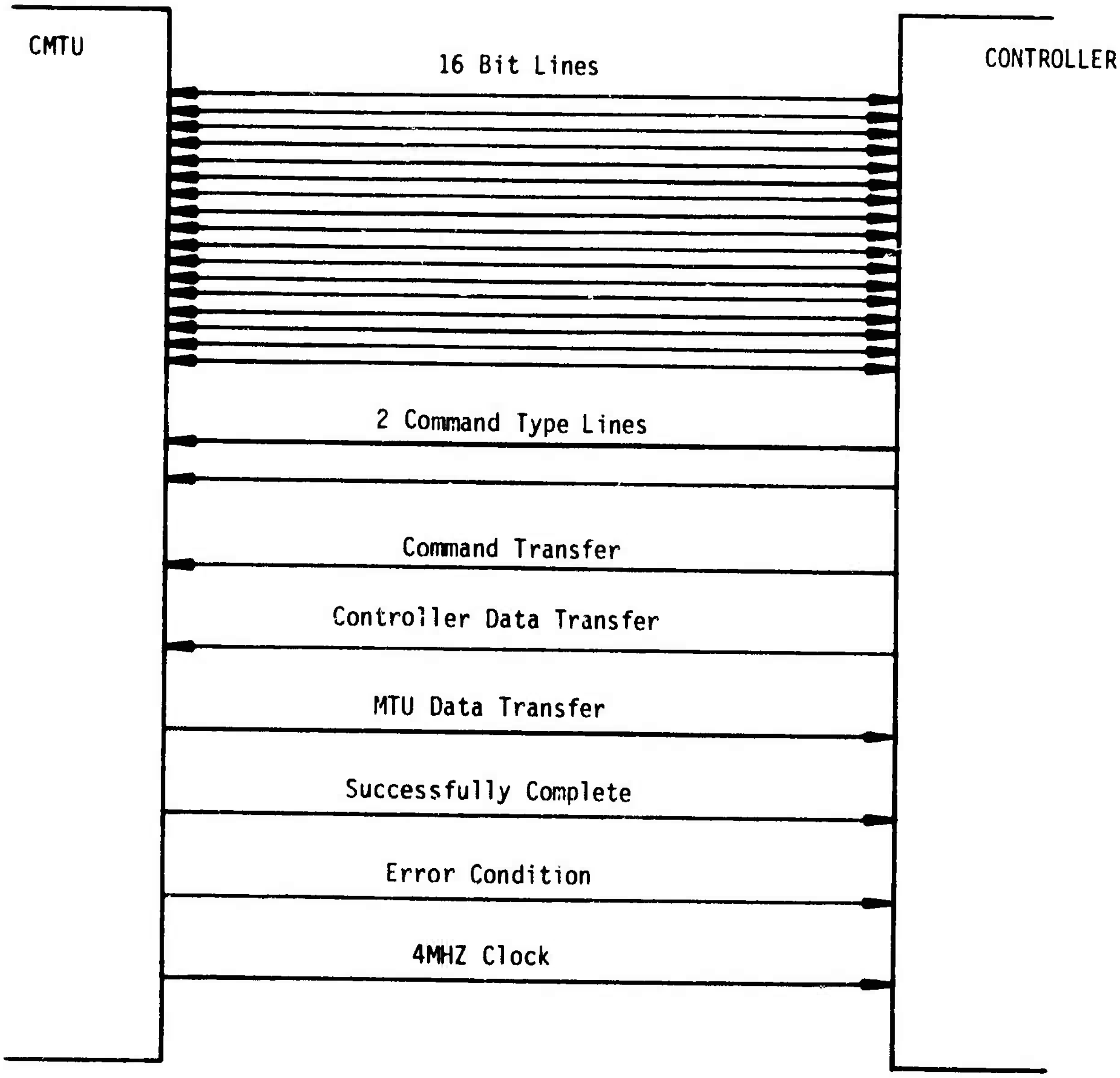


Figure 10: CMTU/Controller Interface

3. CMTU

The Control Multiplex Terminal Unit provides the interface function between the optical bus and the controller. The operation of the CMTU is similar to the MTU except that the CMTU responds to commands received from the controller. The CMTU responds to three different commands from the controller whereas the MTU responds to only two commands. The three commands control the three modes of bus operation.

The CMTU provides the following functions for the control terminal:

1. Provides 4MHz clock to controller
2. Checks incoming status words for:
   - a. correct bit count
   - b. parity
   - c. status error conditions
3. Checks incoming data words for:
   - a. correct bit count
   - b. data dropouts
   - c. parity

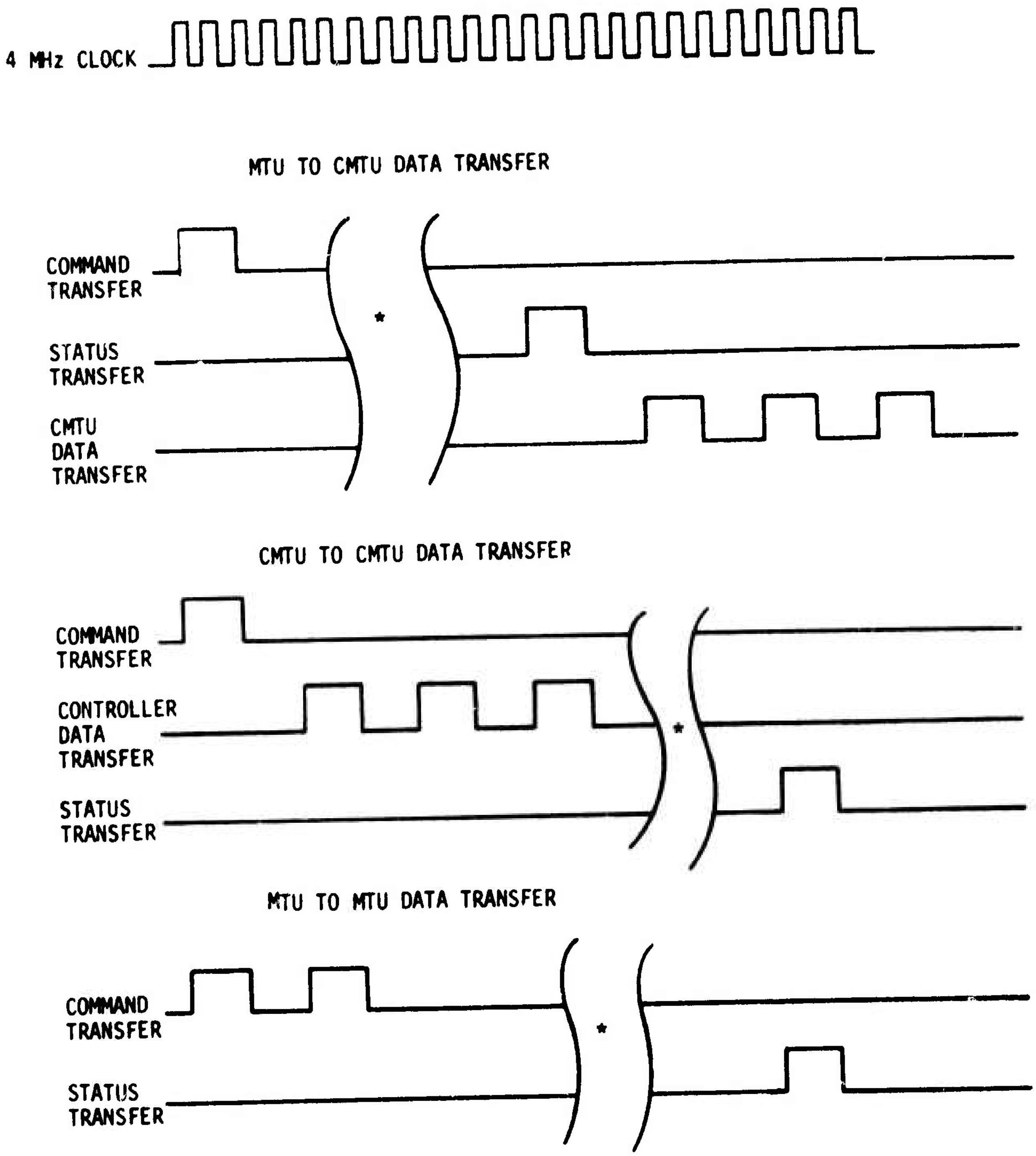
The CMTU/Controller interface consists of control, clock, and bit lines as shown in figure 10. This interface is controlled by the controller through the command transfer line. The interface timing is shown in figure 11.

A simplified block diagram of the CMTU is shown in figure 12. The CMTU is similar to the MTU in operation except that the control commands come from the controller instead of from the data bus. The CMTU also has no address associated with it. The CMTU initiates and controls all bus operation with the supervision of the controller.

The controller directs the CMTU to initiate bus operation by the transfer of one of three types of commands:

(1) Transmit data from controller to remote terminal
(2) Transmit data from remote terminal to controller
(3) Transmit data from remote terminal to remote terminal

The CMTU transmits the appropriate command word, via the data bus, to the desired remote terminal. The CMTU then monitors the data bus for



* Delay Time Required for BUS Transactions

Figure 11: CMTU/Controller Interface Timing

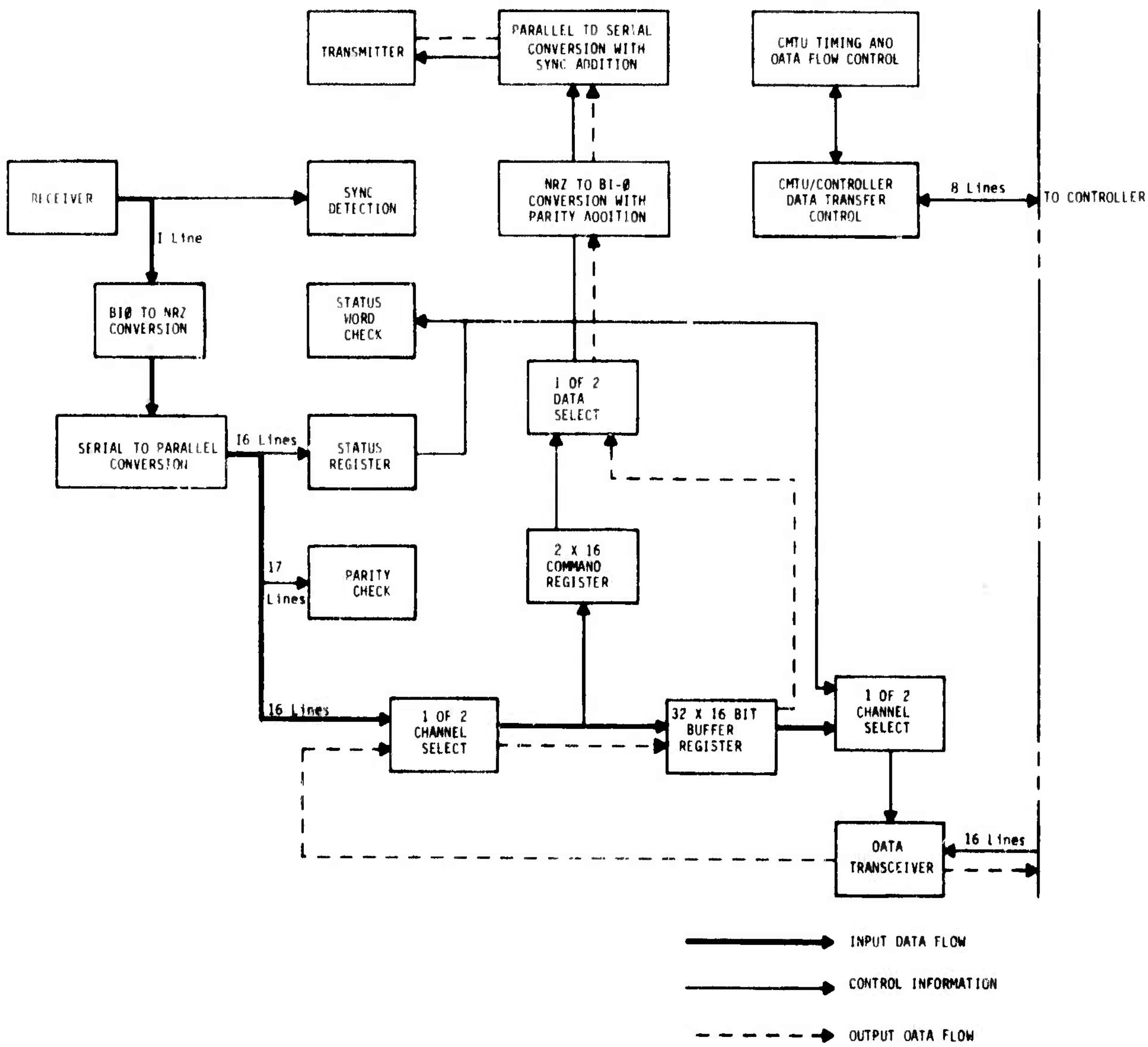


Figure 12: Data Bus CMTU Block Diagram

correct operation by detecting and receiving status words from the remote terminals. These status words indicate the condition of the bus operation with the proper code for correct or error condition. If the status word indicates an error condition, the status word is transferred to the controller via the error condition transfer control. If the status word indicates no error condition, the status word is transferred to the controller via the satisfactory complete transfer control. In the event that no status word is received after a bus command, it is assumed that an error condition occurred in the transmission or the reception of the command word. When this condition occurs no transfer is made between the CMTU and Controller.

In the controller to remote terminal mode, the controller transfers a "receive" command to the CMTU followed by the data words. The CMTU receives the command word and stores it in a command register. It is then converted from a parallel NRZ format to a serial Manchester format with sync addition and trasmitted. The data words are then read from memory and transmitted in the same manner as the command words. The CMTU then detects a positive sync from the incoming status word. The status word is converted from Manchester to NRZ and converted to a parallel word and stored in the status register. The status word is then checked and transferred to the controller.

In the remote terminal to controller mode, the controller transfers a "transmit" command to the CMTU. The CMTU receives the command word and stores it in the command register. The CMTU then transmits the command word to the MTU. The CMTU then receives and stores the status word from the MTU. The status word is followed by the data words which are checked and stored in the buffer memory. After the last data word has been received and sorted the status word is transferred to the controller followed by the data words.

In the MTU to MTU transfer mode, the CMTU receives a receive command word followed by a transmit command word. The CMTU starts transmission of the receive command word to the MTU immediately after it is received. After the transmission of the transmit command word the CMTU receives a status word from the transmit MTU, followed by the data words. The status word is checked and stored. After receiving the last data word, the CMTU receives a status word from the receive MTU. This status word is checked and stored if the first status word contained no error condition as the CMTU only stores one status word at a time. The stored status word is then transferred to the controller.

4. SSIU and Controller

Spectronics has provided three test sets to simulate the interface requirements between the MTUs and CMTU. Two of the test sets simulate the interface between the MTU and SSIU and one simulates the interface of the controller. Interfaces are provided for the SSIU and controller by connectors on the front panel of the MTU and CMTU.

5. Optical Data Bus

Construction of a data bus requires the use of signal coupling devices which make it possible for each station to receive signals from the bus and transmit signals onto the bus. The vital nature of the signal transactions on an avionic data bus dictates that a strong emphasis on system reliability be used in the coupler design. In general, repeater systems are not employed in data buses because damage to one repeater would interrupt signal flow on the entire data bus.

In an optoelectronic data bus, the various stations are interconnected with flexible fiber optic bundles. The desired signal coupling device should provide the following functions:

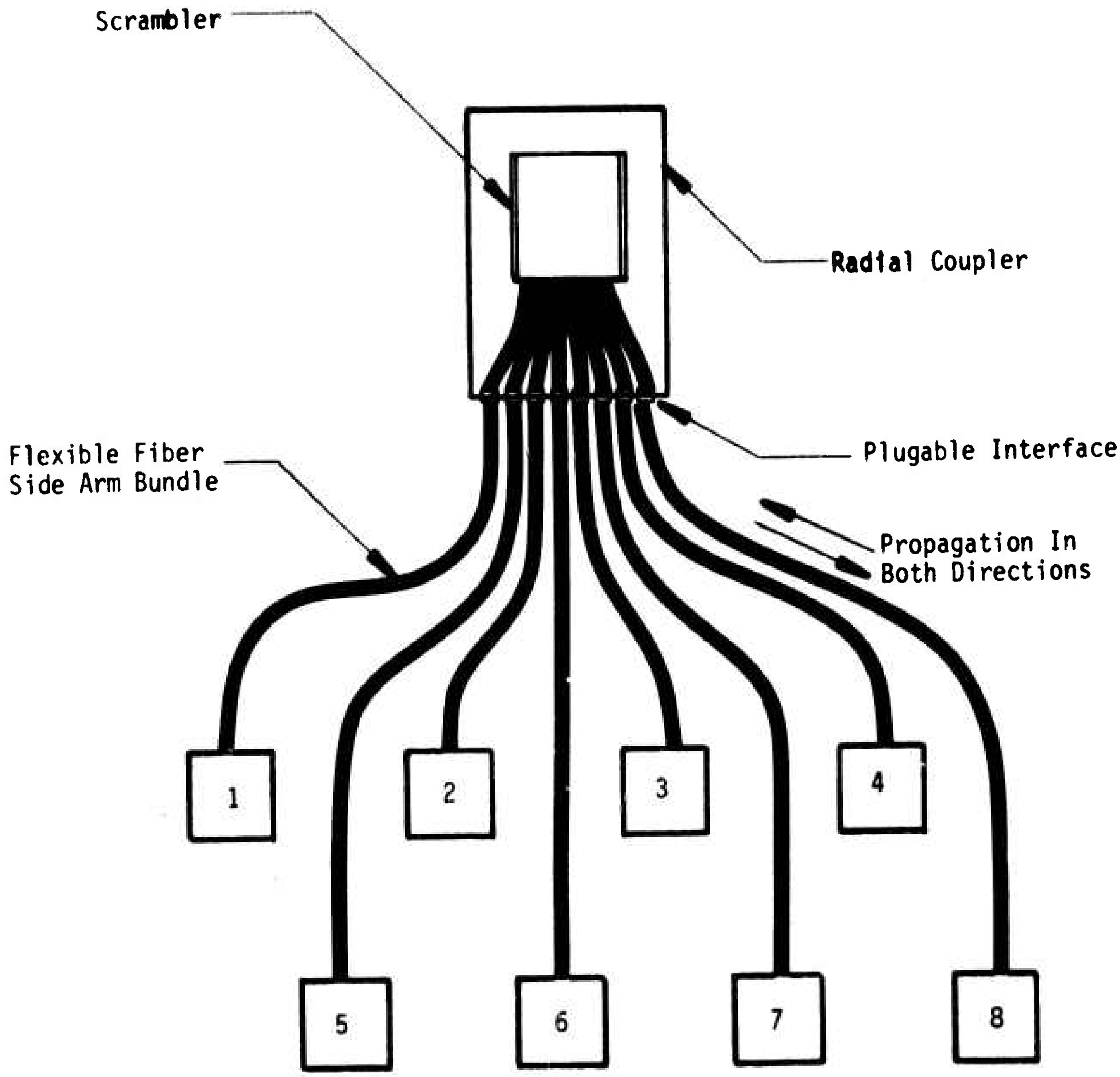


FIGURE 13: Radial Duplex Data Bus

- A portion of the optical signal should be removed from the bus for detection.
- The undetected remainder of the optical signal should be passed on for distribution to the other terminals on the bus.
- Optical signals generated in that terminal should be coupled onto the bus and distributed to the other terminals.

Meeting these requirements provides fault isolation on the optoelectronic data bus so that failure of one of the stations on the bus will affect only that station and will leave the remainder of the bus unimpaired. Two basic schemes have been reported, reference 4 and 5, for providing these functions in an optoelectronic data bus; both schemes have been investigated on this program. One approach uses an in-line configuration in which individual stations are sequentially interconnected by flexible fiber optic bundles. The other approach uses a radial configuration in which all stations are connected by flexible fiber optic bundles to a centrally located mixing point.

The in-line data bus uses a passive T coupler, reference 2, for each station on the bus, where the radial data bus uses a single passive radial coupler. The radial coupler need not be located at one of the stations but can be centrally located between stations to reduce bus length. Figure 13 shows the configuration of a radial duplex data bus.

Since construction of the radial coupler is of approximately the same complexity as construction of a single T coupler and the performance of a radial data bus is superior to the performance of an in-line data bus, in all respects, reference 2 (p 59), except fiber optic cable attenuation, the radial data bus was chosen for use on this program. The continuing development on this program has led to the design of a solid side arm radial coupler that ideally reduces the internal losses to a minimum.

SECTION III
SYSTEM DESIGN AND CONSTRUCTION

The EMI/EMP Data Bus consists of three basic design problems. These three are:

- o Design of optoelectronic interface electronics to convert the optic signals to electrical signals the data processing system can use.
- o Design of an optical data bus capable of handling optical TDM signals between eight stations.
- o Design of a data handling terminal capable of handling the 10M bit/s signal so that a realistic bus can be realized.

Development of the optical bus was done on the first stage of this contract and is discussed in detail in reference 2. The final design of the optical bus is presented in this section.

The unique problems associated with the optical unipolar signal are presented in the optoelectronic interface section and the construction details of the data manipulation portion is described in the Data Processing Section.

1. Optoelectronic Interface Design

Fiber optic data transmission systems using non coherent LEDs and p-i-n photodiodes present a different problem than wire systems. Light emitted from an LED is not coherent and must therefore be treated as a photon flux or power, reference 3 (p 5). Thus, a modulated LED emits a time varying power that has no negative values. Because the light output of an LED can be only zero or positive, an optical Manchester signal is unipolar with its average value equal to half the peak. The conventional Manchester signal used in wire data buses is bipolar with equal positive and negative excursion and an average value of zero. Figure 14 shows a comparison of bipolar and unipolar Manchester signals.

The threshold level of the conventional bipolar Manchester signal is independent of the data content and signal amplitude, however this is not the case for the unipolar Manchester signal. The unipolar Manchester signal threshold is independent of data content but is dependent on signal level. For the AC coupled unipolar signal the threshold level is the average value of the signal, which for the Manchester signal is one half the peak signal amplitude in the steady state condition. The operation of the data bus however, does not allow for the steady state condition to exist for very long as the signal levels received, vary from no signal to large and small signals. This dynamic range causes a severe problem that is illustrated in figure 15. For a transaction with a near station, the signal is large and the input coupling capacitor charges up to the average value of the signal. If this is followed by a transaction with a distant station where the signal is small, the coupling capacitor discharges to the new average value. This signal is difficult to decode as the reference level in the receiver must constantly change with the incoming signal level changes.

Dynamic range in a direct coupled receiver causes a different problem than was described above in the ac coupled receiver. Figure 16 shows typical waveforms for a weak signal and a strong signal. These waveforms are typical for 10M bit/s with a system bandwidth (3dB) of 10.0MHz. The threshold is set to properly detect the weak signal; however, stronger signals will not be symmetrical about the threshold and a strong signal 12.5 times larger than the weak signal will have no portion of its waveform fall below the threshold level. This deficiency can be overcome by increasing the system bandwidth to give faster rise and fall time on the signal waveforms. With faster rise time the signal will come closer to the steady-state "on" or "off" level during each half bit time and more dynamic range can be accommodated. However, optimized preamps have an equivalent input noise current that is proportional to bandwidth. For a constant error rate the required signal power on the detector is proportional to the amplifier bandwidth.

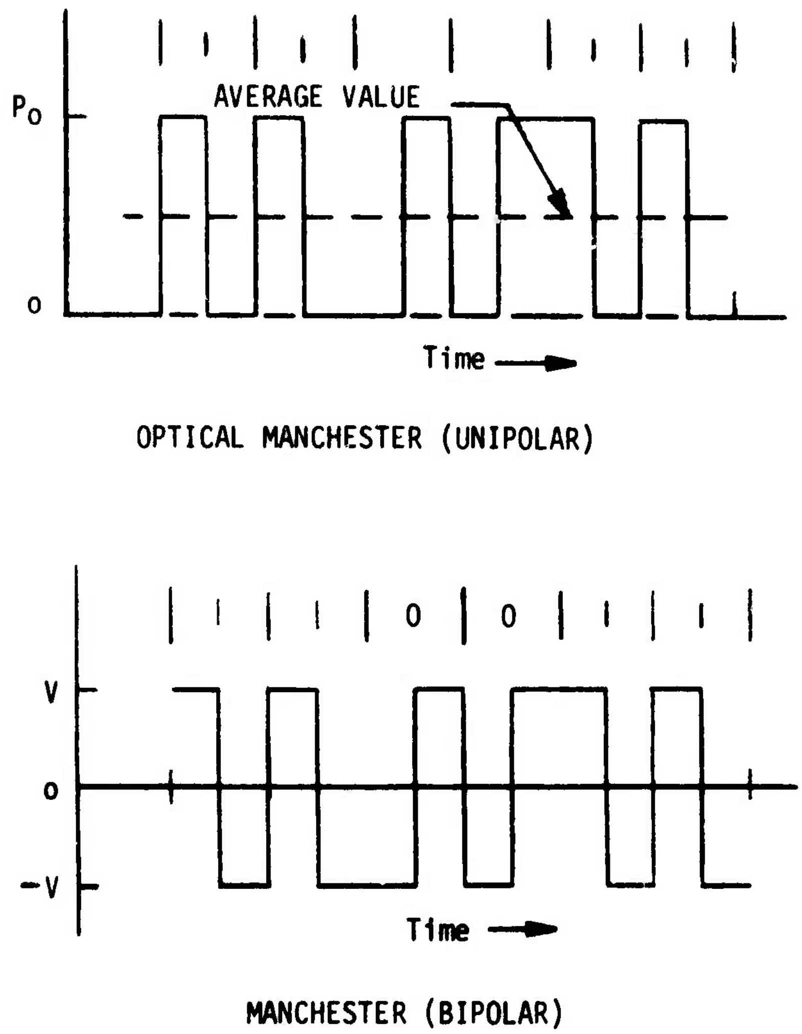


Figure 14: Comparison of Optical and Electrical Manchester Code

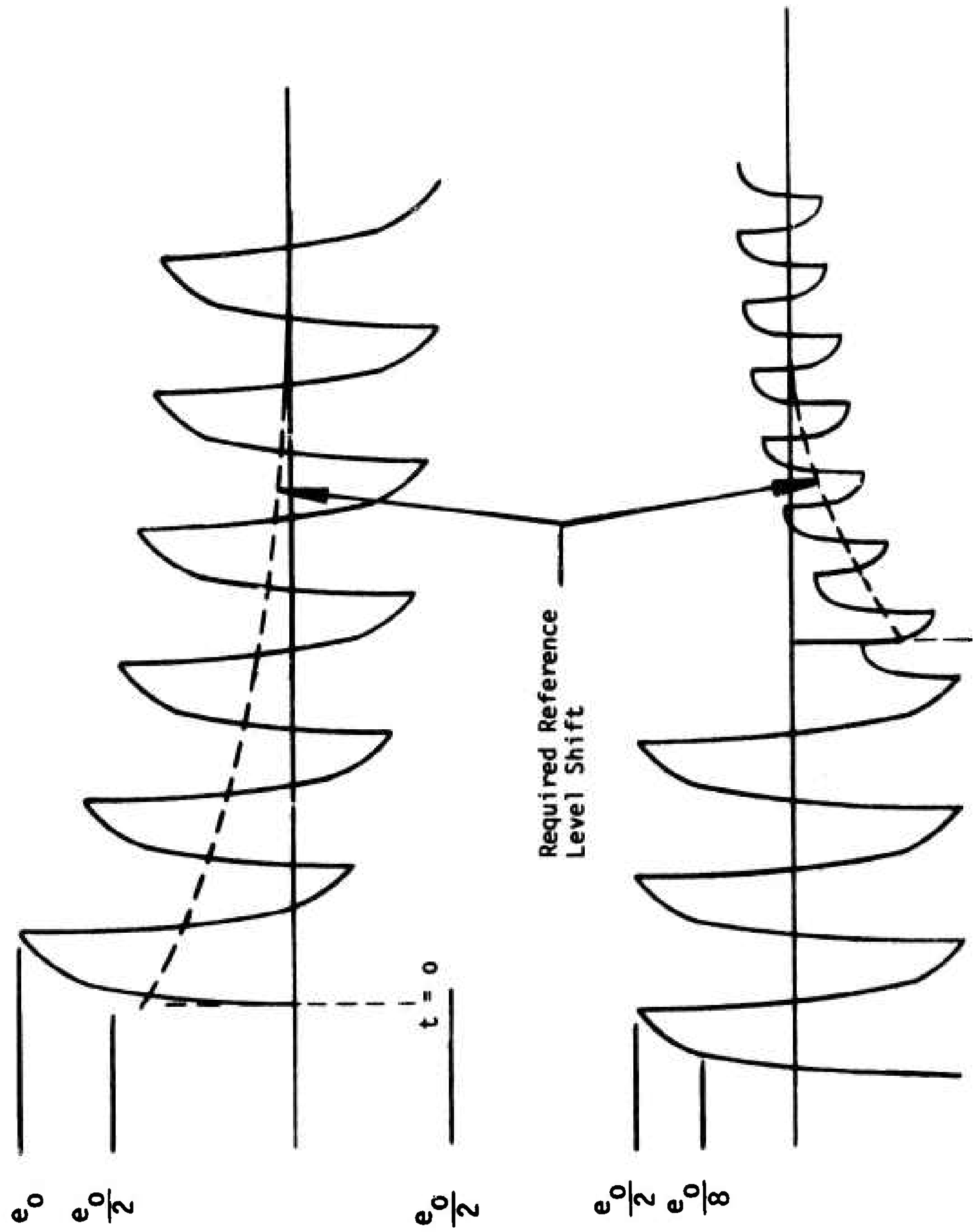


FIGURE 15. AC COUPLED SIGNAL SHIFT

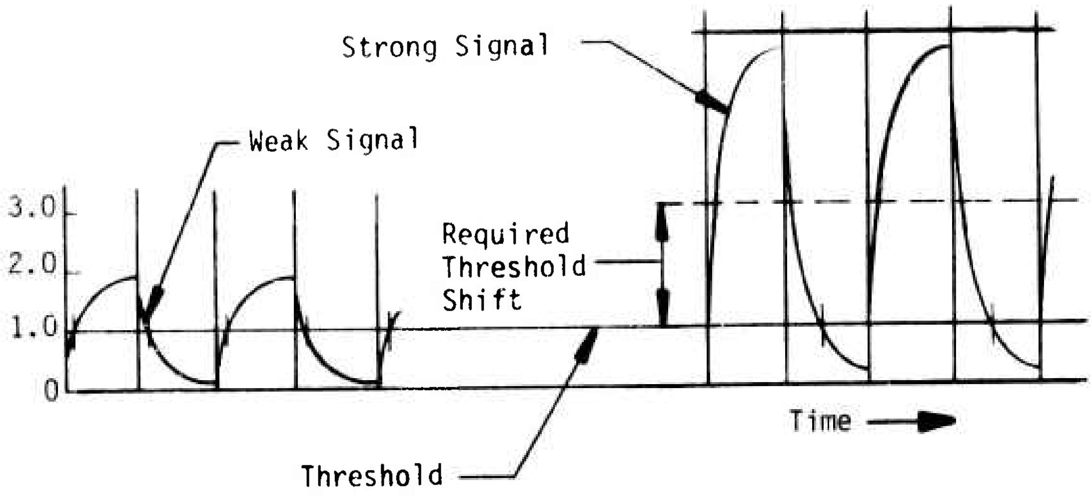


Figure 16. Signals in a Direct Coupled Receiver

Another approach that can overcome the difficulties in the dc coupled receiver is to shift the reference level with changes in signal amplitude. This is done with a peak detector that is reset between message transmissions.

The other problem in direct coupling is the presence of drift as a possible source of error. The drift in an optimized 10M Hz preamp requires 2 times more minimum optical power, reference 2 (p 65) on the detector than is required with an ac coupled receiver with the same bandwidth.

The block diagram of the receive optoelectronic interface used to solve the problem of the optical unipolar signal is shown in figure 17 and consists of the following sections

Photodiode
Preamp
Postamp
DC Restoration
Buffer Amp
Peak Detector
Comparitor
Delay Detector

To provide for optimum S/N ratio the preamp and postamp are ac coupled to eliminate the drift, reference 2 (p 63), as a possible source of error. Further, since the dc coupled signal is easier to detect than the ac signal, the ac signal is restored again to a dc level.

Detection of the dc restored signal is made by the peak detection circuit and the comparator. The peak detector sets a reference level of 1/2 the peak incoming signal. This reference level is provided to one of the comparator inputs to provide a proper threshold for proper decoding of the input signal.

The output of the comparator is monitored by a delay detector. This delay detector monitors the end of a message by detecting the delay between transmissions of different terminals. When a delay is detected the peak detector is reset so that the next message can be detected.

The block diagram for the transmit optoelectronic interface is shown in figure 18. It consists of two sections:

- LED
- LED Driver

The LED driver uses the speed-up techniques of reference 3 (p 42).

a. LED

The LED used in the data bus is a planar GaAs edge emitter manufactured by Spectronics, Inc. The basic LED shown in figure 19 carries the part number SPX 1775. This device was specifically designed for coupling to .045 - .050 in diameter fiber optics bundles. The coaxial package configuration of the device provides for EMI shielding and low thermal resistance, $\leq$ 100°C/W. The edge emitting wafer with optimized collimating reflector provides for a high efficiency source with a narrow beam angle.

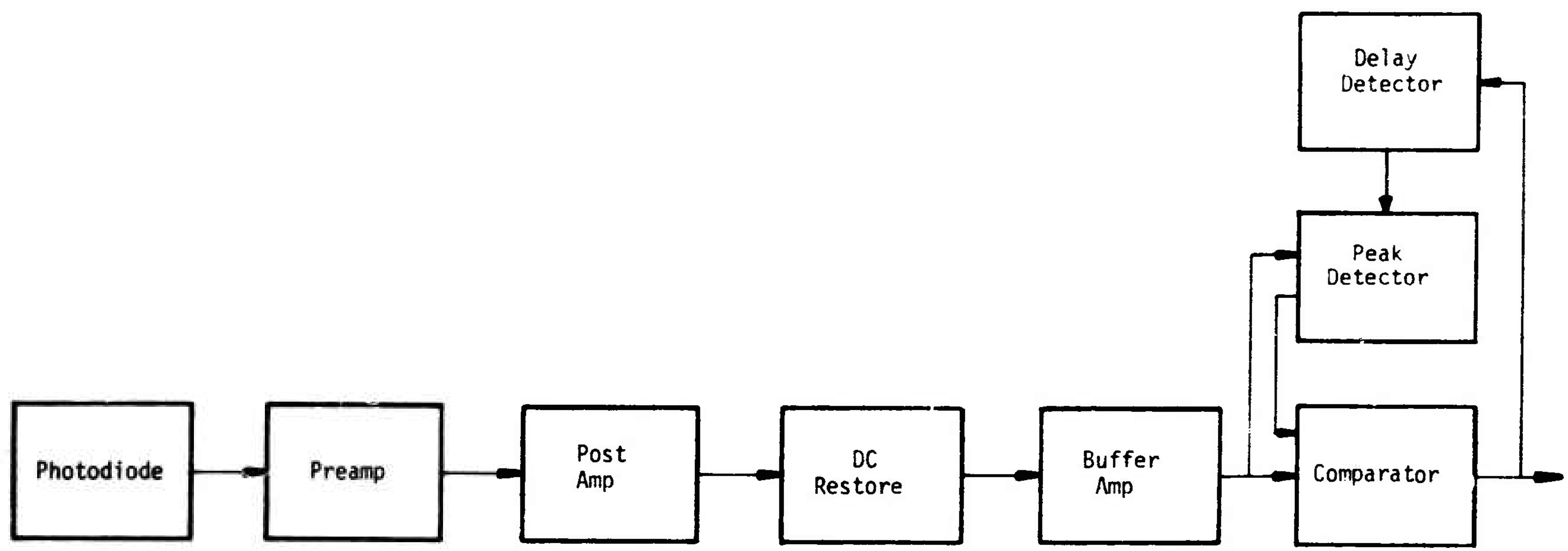


Figure 17: Receive Optoelectronic Interface

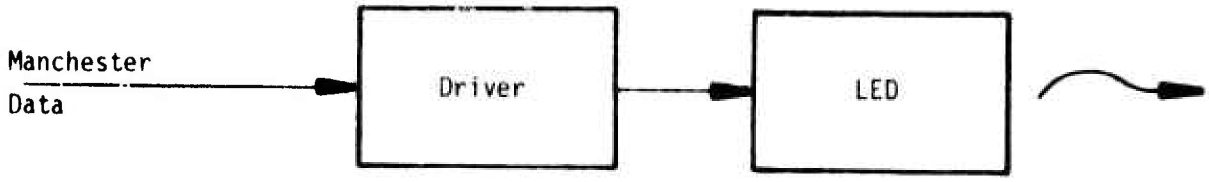


Figure 18. TRANSMIT OPTOELECTRONIC INTERFACE

Typical total power output for the devices used on the data bus is 2.5 to 3 milliwatts @ 100ma of bias current. The LEDs were selected with rise times of 30ns as the slower devices have higher output power. The 30ns rise time of these devices is not adequate for the 10 MHz Manchester data rate so a 2 to 1 speed-up network is used in the LED driver. This increases the LED rise time to 15ns. The data bus efficiency is 66%, so with the 50% duty cycle in the on time the actual duty cycle will be 33% maximum. This gives approximately 200mW power dissipation in the LED. Because of this power dissipation, it is necessary to heat sink the LED adequately to make use of the good thermal resistance characteristics of the LED package so the junction temperature rise is minimized. For a 200mW power dissipation, the junction temperature will rise 20°C above the heat sink temperature.

b. Photodiode

The photodiode used in the data bus is a p-i-n photodiode manufactured by Spectronics, Inc. The photodiode shown in figure 20 has the same package configuration as the LED. This device was also specifically designed for coupling to fiber optic bundles up to .050 inches in diameter. Table 3 gives a summary of the SPX 1777 specifications. This photodiode is designed so that the entire thickness of the wafer is depleted at a reverse bias of 90V. Operation at full depletion gives minimum capacitance, minimum series resistance, and essentially eliminates the slow tail response, reference 3 (p 138).

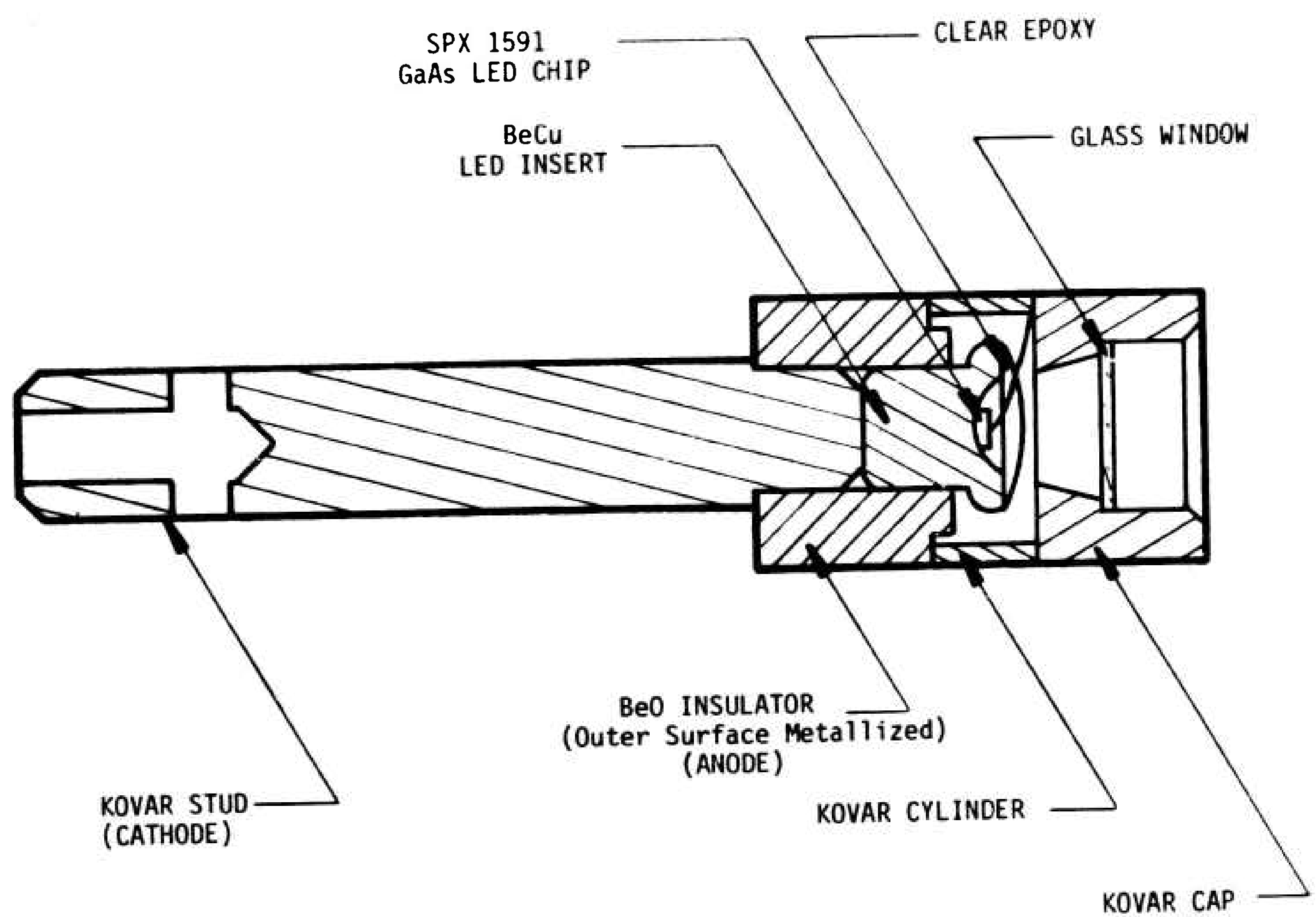


Figure 19: SPX 1775 LED, 12:1 Scale

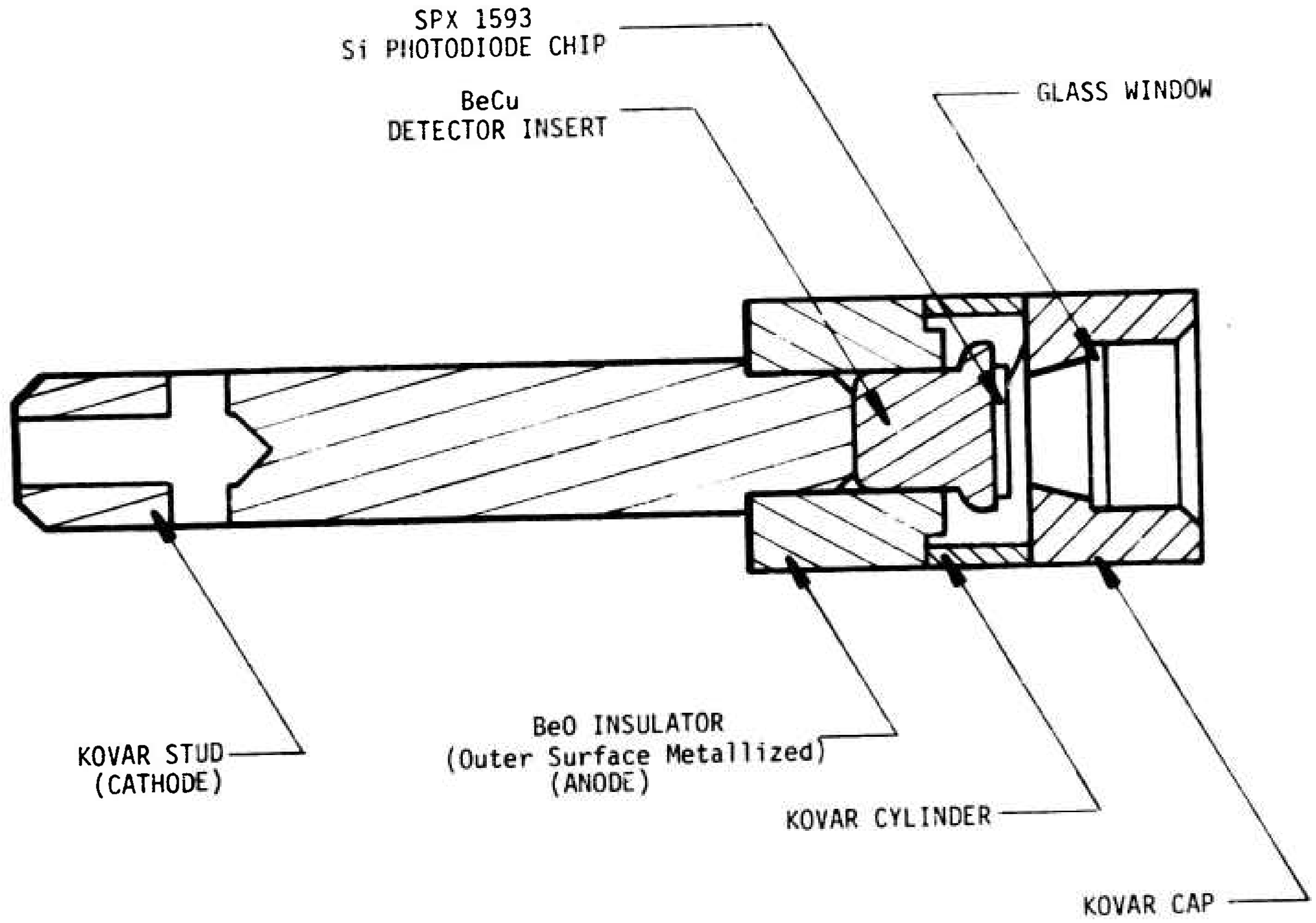


Figure 20: SPX 1777 Photodiode, 12:1 Scale

TABLE 2. SPX 1775

Description: GaAs edge emitting LED

Optical/Electrical Specifications @ 25°C

	Min	Max	Typical
Reverse breakdown voltage @ I_R = 10μa	4.0V		
Forward voltage A I_F = 100ma		1.5V	
r_s			1.0Ω
C_T @ V_R + 1V, f = 1MHz			12pf
τ_ρ @ 100ma			907nm
$\Delta\tau$ @ 100ma			22nm
Power out	2.0mW		
Θ = 15° half angle $f_o P_\theta$			1mW
tr			20ns

TABLE 3. SPX 1777

Description: PIN Photodiode, Coaxial package

Chip thickness .004 in (nominal)

Active Area .050 in diameter

Optical/Electrical Specification @ 25°C

	Min	Max	Typical
Reverse breakdown voltage @ I_R = 10μa	180V	200V	
Dark Leakage current @ V_R = 90V		20na	1na
Total capacitance @ V_R = 90V		4.2pF	
1MHz @ V_R = 30V		5.2pF	
Responsivity @ 907nm	0.5A/W		
Rise Time (10-90%) @ V_R = 90V		1.5ns	
Series Resistance (cal) @ V_R = 90V		15Ω	

c. LED and Photodiode Mounting

The LED and photodiode were mounted in a modified DED connector manufactured by ITT Cannon Electric Division. This connector shown in figures 21 and 22 was modified by ITT Cannon to specifically house these devices with the mating half housing the fiber optics cables to provide a plugable optical interface at the front panel of the MTUs and CMTU as shown in figures 23 and 24.

The LED and photodiode are first soldered into the retaining clip shown in figure 21. These clips provide an electrical contact for the anode of the LED and detector. These device retaining clip assemblies are inserted into the rear of the connector insert. This insert is aluminum and is hard anodized to provide electrical isolation for the LED while still providing a good heat sink. The photodiode is further isolated from the anodized insert by a plastic cylindrical insert.

The devices are held into the connector with an "O" ring, cylinder combination. The "O" ring is first slipped over the cathode contact of the device and is then followed by the plastic cylinder. Pressure is applied to the cylinder by the plastic retaining insert which is held into the connector assembly with screws. The "O" ring takes up the dimensional tolerances in mounting and also absorbs axial loading pressures incurred when the connector is mated with half containing the fiber optic bundles.

Provisions are made to connect the aluminum insert to signal ground to provide for EMI shielding and to prevent cross talk between the transmitter and receiver. This connector assembly is connected to the front panel of the MTU with the back section extending into a partitioned RF enclosure that provides further isolation between the transmitter and receiver. Figure 27 shows the rear of the front panel with the device contacts extending into their appropriate RF enclosure.

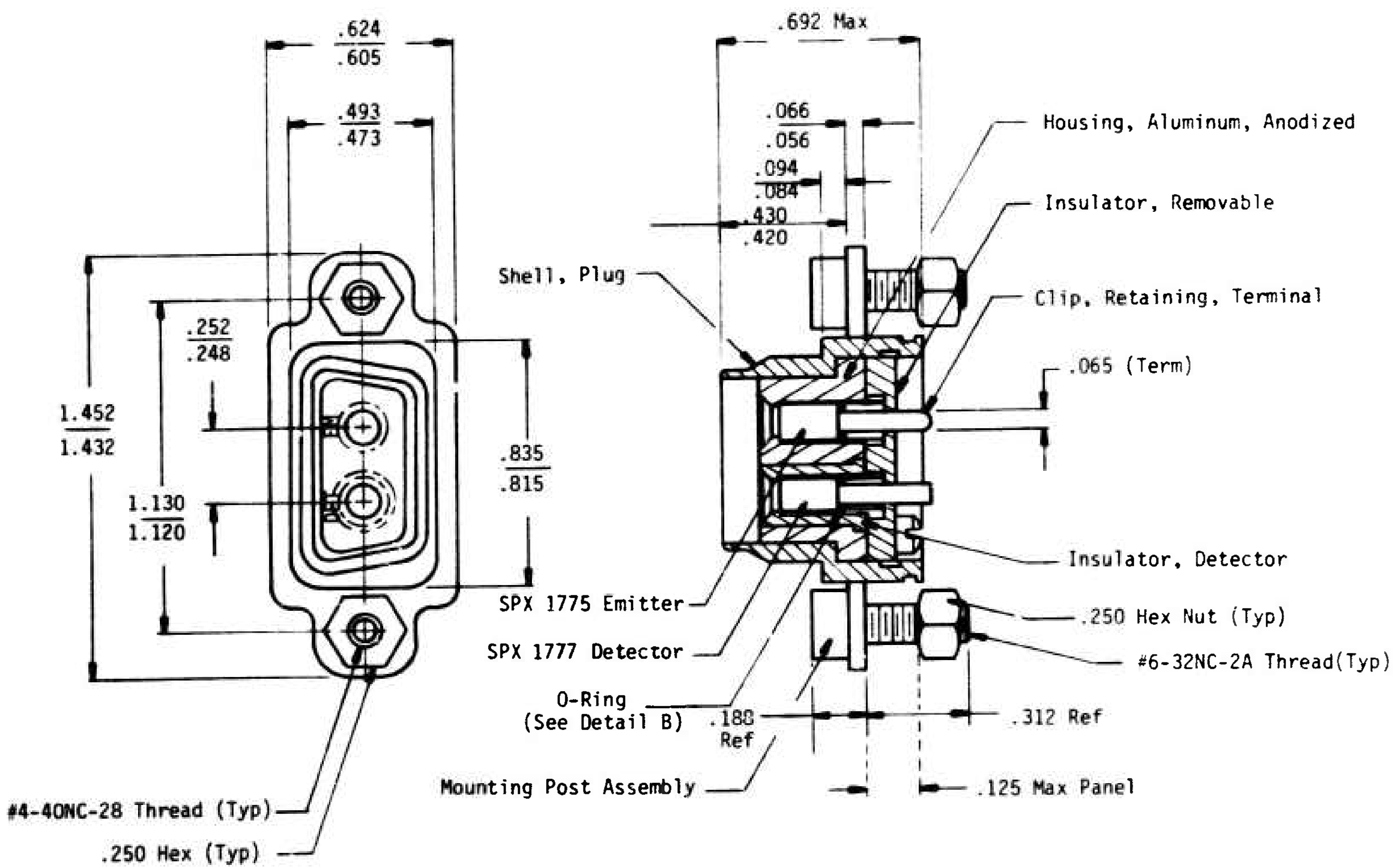


FIGURE 21: DED CONNECTOR

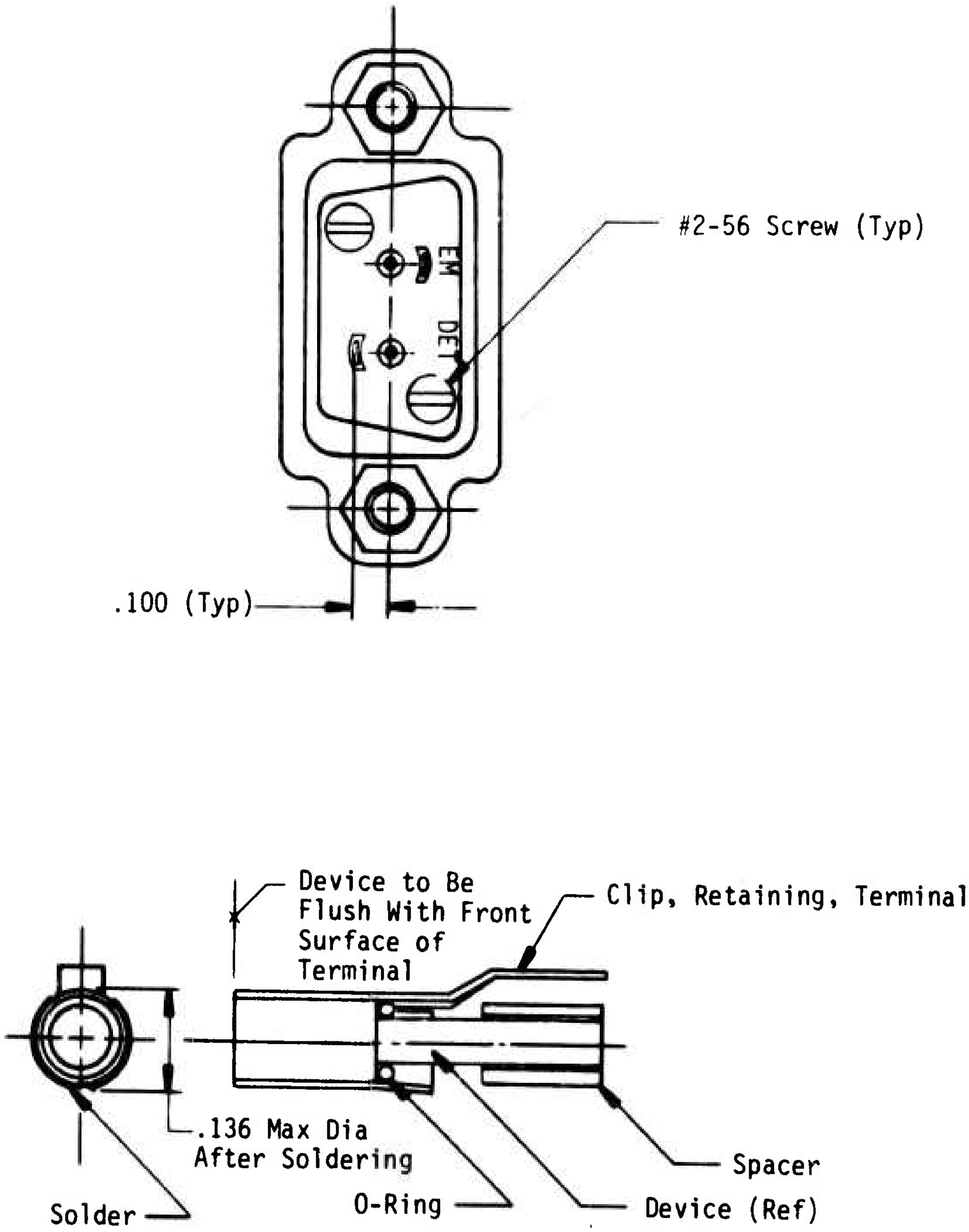


Figure 22: DED Connector (Rear View)

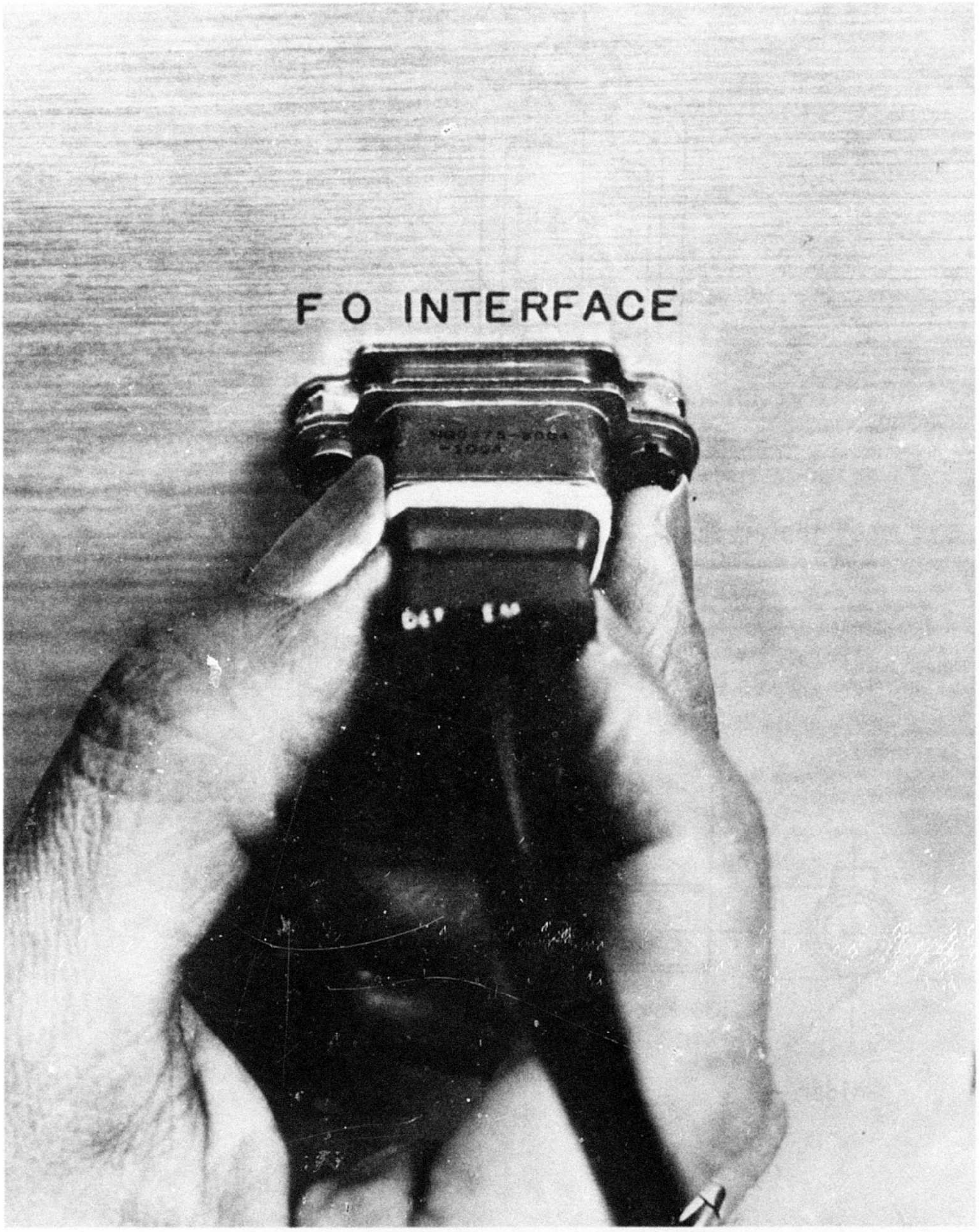


Figure 23: Pluggable Optical Interface

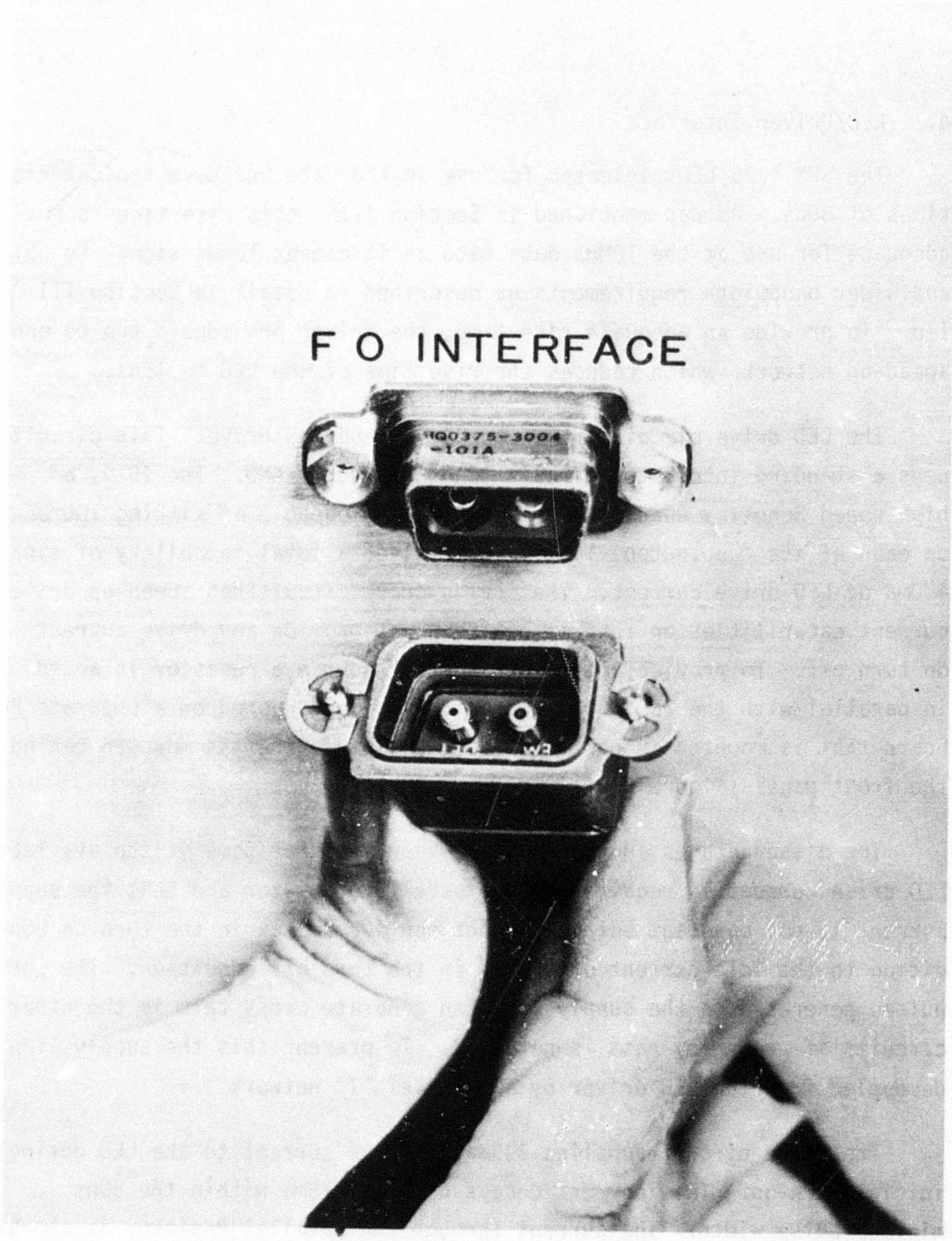


Figure 24: Pluggable Optical Interface (Disconnected)

d. LED/Driver Interface

The SPX 1775 LEDs selected for use in the data bus have typical rise times of 30ns. As was mentioned in Section IIIA, this rise time is not adequate for use at the 10MHz data rate as it causes lower signal to noise and wider bandwidth requirements as described in detail in Section III 1-e. To provide an adequate rise time, the driver provides a two to one speed-up network which reduces the rise time of the LED to 15ns.

The LED drive circuit of figure 25 uses series drive. This circuit uses a standard integrated circuit manufactured by AMD. The IC is a high speed Schottky quad line driver/receiver capable of sinking 100ma on each of its four output lines. This gives a total capability of sinking 400ma of LED drive current. The series drive circuit has speed-up drive current capabilities on turn on but does not provide any drive current on turn off. To provide a turn off current source a resistor is added in parallel with the LED. The LED driver is constructed on a separate PC board that is mounted in partitioned RF enclosure that is mounted behind the front panel (figure 27).

The disadvantages in the series driver are that some of the available LED drive current is required by the parallel resistor and that the supply current is not constant but varies between 400ma peak in the turn on condition to the idle current of the IC in the turn off condition. The current pulses generated on the supply line can generate cross talk in the other circuits if proper by-pass is not used. To prevent this the supply line is decoupled from the LED driver by a parallel "T" network.

The drive circuit supplies 345ma of drive current to the LED during initial turn-on. This current decays back to 175ma within the 50ns minimum pulse width. The current through the parallel resistor is approximately 55ma during the on-time so the drive circuit sinks 400ma during initial turn-on. This current decays back to 230ma.

e. Preamp

The preamp used in the data bus is similar to the transresistance preamp described in reference 3 (p 14). The preamp uses a monolithic transistor array manufactured by RCA. The device is a CA3127E and contains 5 transistors. These transistors have an f_T of 1.1 GHz @ I_E = 1ma and V_{CE} = 5 volts.

Figure 26 shows the schematic of the preamp used in the data bus. The basic circuit is a transimpedance (current mode input) design having a cascode input stage and shunt feed-back. The cascode input reduces the Miller effect capacitance due to the collector-base capacitance. Three transistors are required to build this amplifier, so the two spare transistors are used as zener diodes, to provide required reference signals. This simplifies construction by reducing component count. The preamp is constructed on a separate circuit board as is shown in figure 27. This preamp circuit board is mounted on the back of the front panel in one half of the partitioned RF enclosure. This allows the photodiode to be connected directly to the preamp which reduces stray pick up and provides good EMI protection.

Determination of the optimum preamp bandwidth for operation of the 10M bit/s data bus system is not easily determined from the suboptimum detection scheme discussed in reference 3 (p 27). The data bus uses peak detection for providing a reference level for decoding the signal. Also the data bus must derive clock from the data so that clock errors can occur in strobing the data. However for simplicity, suboptimum detection is used for a starting point where it is assumed that there are no clock errors and the data is strobed at the T/2 point.

Using the above assumptions, the worst case signal to noise is analyzed. For a suboptimum detection scheme, the presence of the "f^2" noise dictates that the amplifier must have at least two poles in the high frequency cutoff characteristic so that the total noise will be bounded. The low frequency pole at f_o is determined by the feedback network of the preamp with the second pole, f_2, set at 1.85 f_o by the

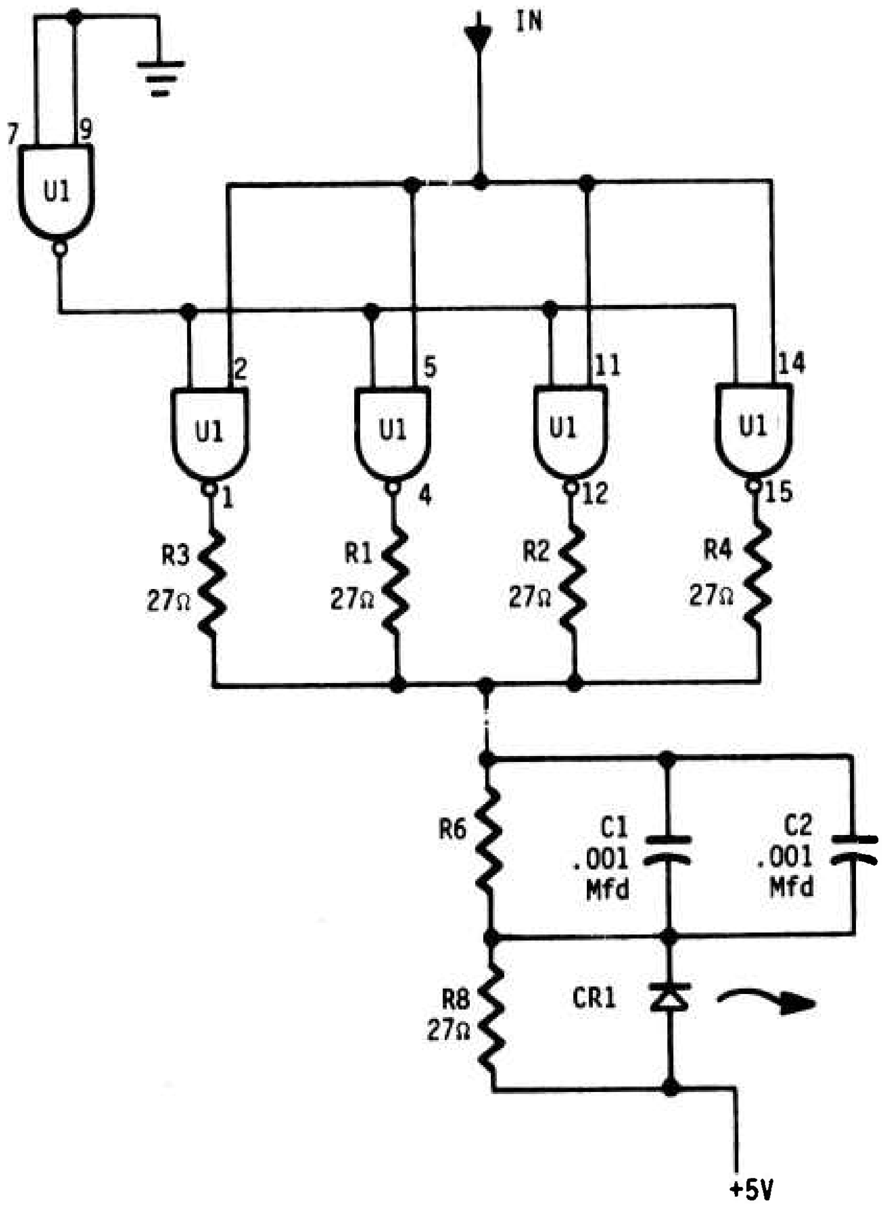


Figure 25: LED Driver

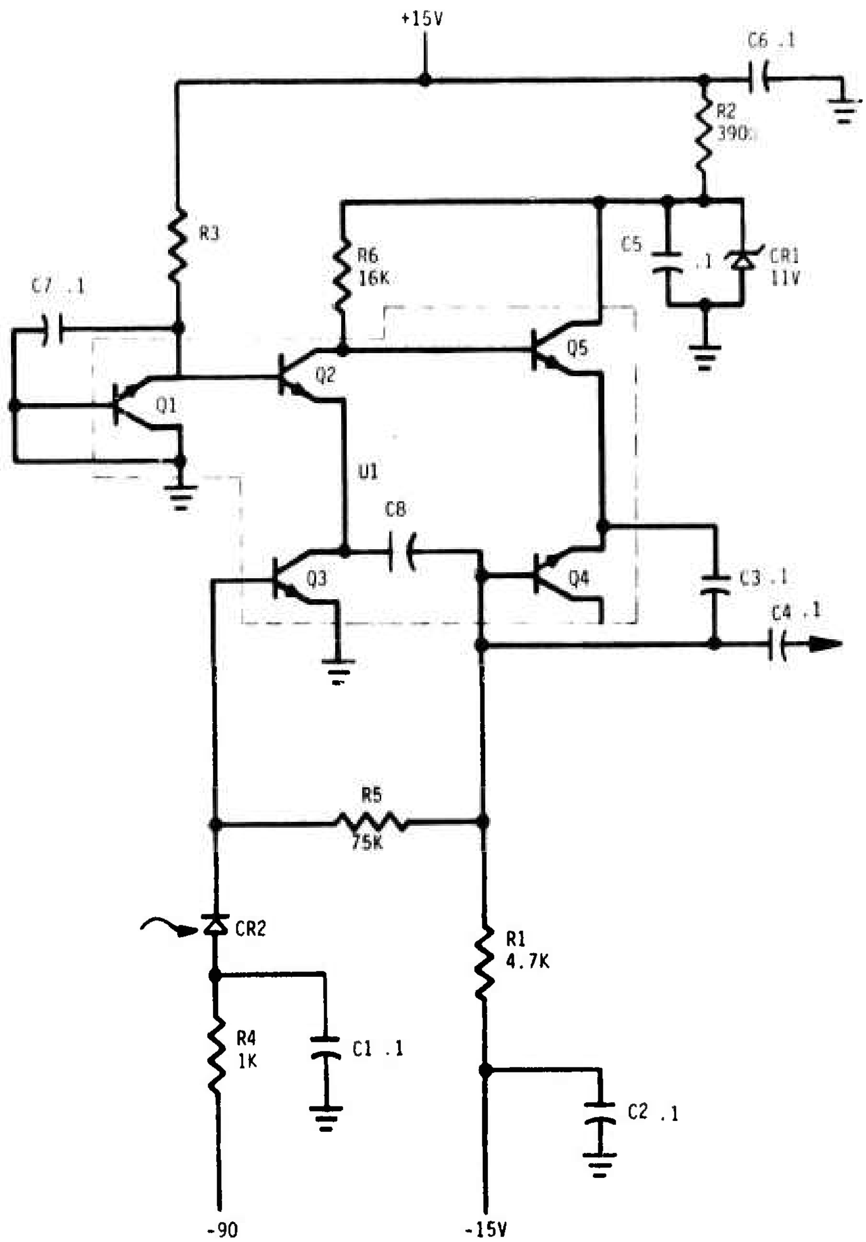


Figure 26: Preamp Schematic

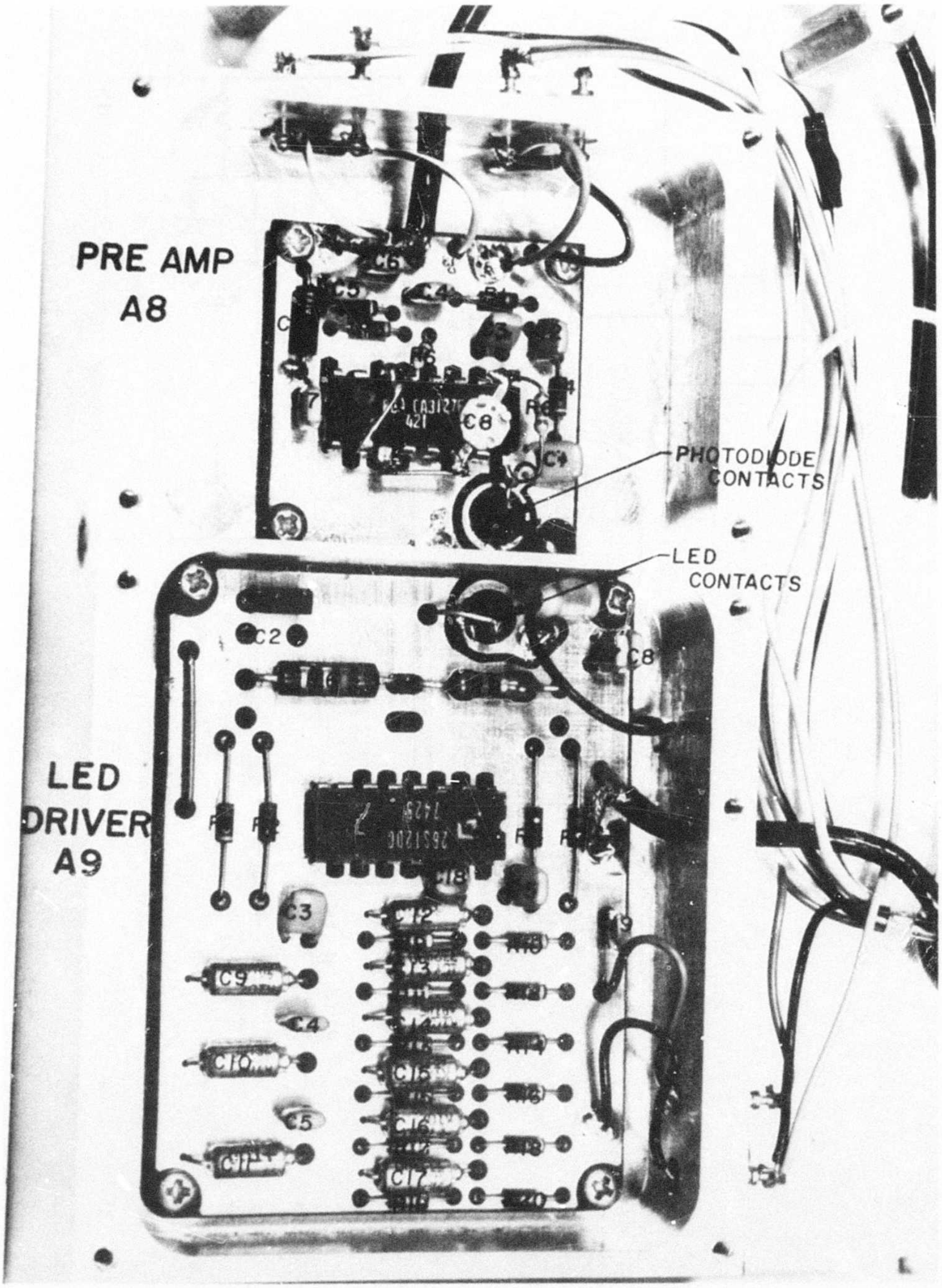


Figure 27: Preamp & LED Driver Mounting

post amp, reference 3 (p 15). The reference level will be set at one half the peak signal by the peak detector. This peak signal can be limited by the bandwidth of the amplifier chain if the rise time is not fast enough to allow the input signal to reach its maximum value. The peak detector will be set by the sync pulse as this pulse is three times wider than the minimum half bit pulse of 50ns.

The transfer function of the amplifier chain is:

$$\left(\frac{1/\tau_o}{s + 1/\tau_o}\right)\left(\frac{1/\tau_2}{s + 1/\tau_2}\right) \quad (1)$$

Assuming a step input signal is received from an LED with zero rise time, the output signal is equal to input signal times the inverse Laplace transform of the following function:

$$e_{out} = e_{in} \mathcal{L}^{-1} \frac{1}{s}\left(\frac{1/\tau_o}{s + 1/\tau_o}\right)\left(\frac{1/\tau_2}{s + 1/\tau_2}\right) \quad (2)$$

which, if $\tau_o = 1.85\ \tau_2$ eq (2) equals

$$e_{out} = e_{in}\left(1 - \frac{1.85}{.85} e^{-t/\tau_o} + \frac{1}{.85} e^{-t/1.85\tau_o}\right) \quad (3)$$

The S/N ratio is the difference between this signal at the T/2 point (or t = 50ns) and the reference level of 1/2 the input (or $e_{in/2}$) divided by the noise voltage (e_n). Equation 3 then reduces to:

$$S/N = \frac{e_{in}}{e_n}\left(.5 - \frac{1.85}{.85} e^{-50/\tau_o} + .85_e^{-50/1.85\tau_o}\right) \quad (4)$$

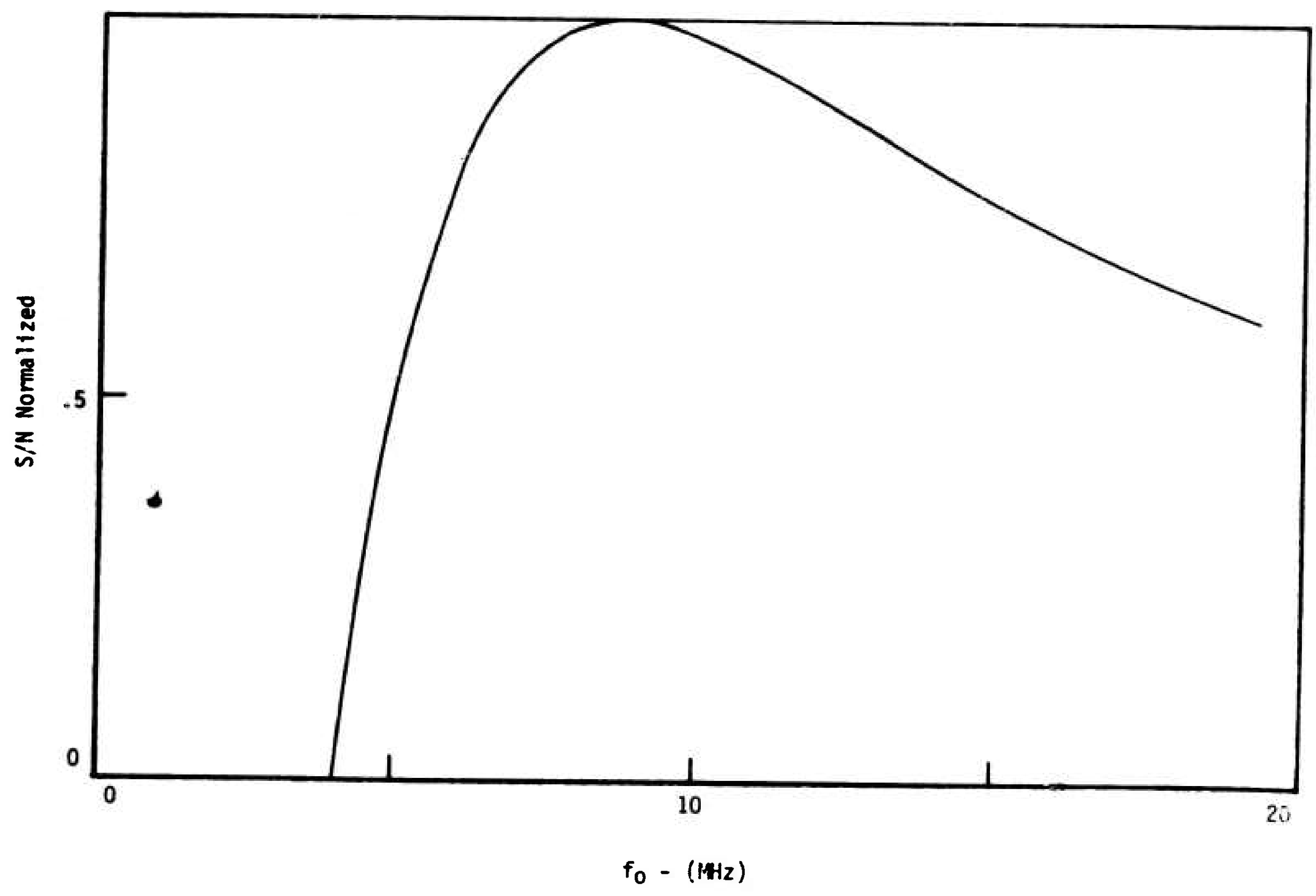


FIGURE 28: Plot of S/N vs. f_o Ideal LED

where τ_o is in ns

If e_n increases linearly with bandwidth then e_{in}/e_n is normalized at a maximum signal to noise ratio and equation (4) reduces to:

$$\text{S/N normalized} = \frac{.5 - \frac{1.85}{.85} e^{-50\tau_o} + .85\, e^{-50/1.85\tau_o}}{\tau_{max}/\tau_o} \qquad (5)$$

where τ_{max} is the time constant for Equation (4) that gives maximum S/N ratio.

Since f_o is related to τ_o by:

$$f_o = \frac{1}{2\pi\tau_o}$$

Equation (5) is plotted as f_o vs S/N as shown in figure 28.
Solving (5) for its maximum value gives:

$$\text{S/N} = \text{S/N max at } \tau_o = 18.7\text{ns}$$

$$f_o = \frac{1}{2\pi\tau} = 8.53\text{MHz}$$

The graph in figure 28 shows there is a definite optimum bandwidth for the Data Bus system. It also shows that the S/N ratio falls off rapidly if the system bandwidth is reduced, however, the S/N ratio does not fall off fast if the bandwidth is increased. If the bandwidth is reduced by a factor of 2, the S/N is reduced to .154 of its optimum value while the S/N is reduced to only .684 of the optimum value if the bandwidth is increased by a factor of 2.

The above example is assumed to be a good model for the receive section of the Data Bus System, however, the model assumes that the transmit section has a 0 rise time. To get the overall optimum bandwidth, the rise time of the LED and driver must be included in the above example. The model used for the LED is exponential with the same 10% to 90% rise time as the LED. Although this is not a true model of

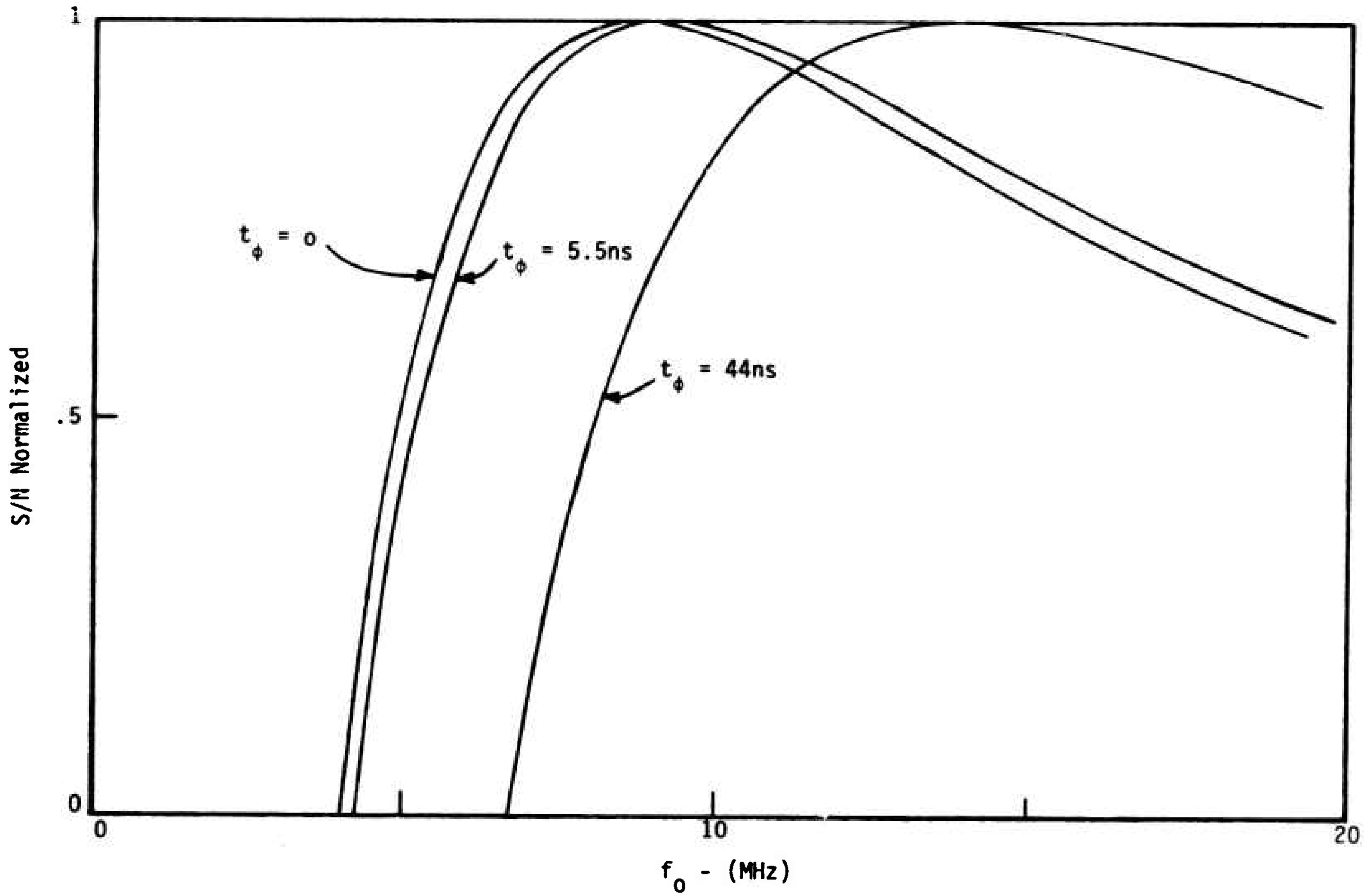


Figure 29: Optimum Bandwidth With LED (t_ϕ) Risetime

the rise time of the LED, it will be used to represent a worst case condition. Expanding Eq. (5) gives:

$$S/N = \frac{.5 - [1.85C/(.85(C-1\tau_o)]e^{-t/\tau_o} + [C/(.85(C-1.85/\tau_o)]e^{-1.85/\tau_o} - [9.85/(C\tau_o\ 01.85)(C\tau_o-1)]e^{-Ct}}{\tau_{max}/\tau_o} \quad (7)$$

where $C = 1/\tau\phi$, $\tau\phi$ = time constant of LED.

Figure 29 shows the effect the third pole has on the optimum bandwidth of the system. Two plots of the above equation are shown in figure 29, one with a LED rise time of 5.5ns and one with a LED rise time of 44ns. These plots are also compared with the plot of equation (5).

Figure 29 only shows the optimum bandwidth that will give maximum signal to noise for that set of conditions. It does not show the actual effects the LED rise time has on the S/N ratio as each equation is normalized with its own maximum S/N ratio. To calculate the actual S/N eq (4) would have to be expanded to include the effects of the LED and then evaluated at $\tau_o = \tau_{max}$.

f_o was chosen to be 12.5MHz for the data bus preamp as this gives a total preamp system rise time of approximately 30ns and with an LED, with a rise time of 15ns, will give a total system response of approximately 35ns.

2. Optical Bus

a. Radial Coupler

The coupler development portion of this contract led to the design and construction of a radial coupler which ideally minimizes the loss in this type of device. The coupler is constructed with square side arms and a square scrambler rod. It is housed in a modified rectangular connector housing.

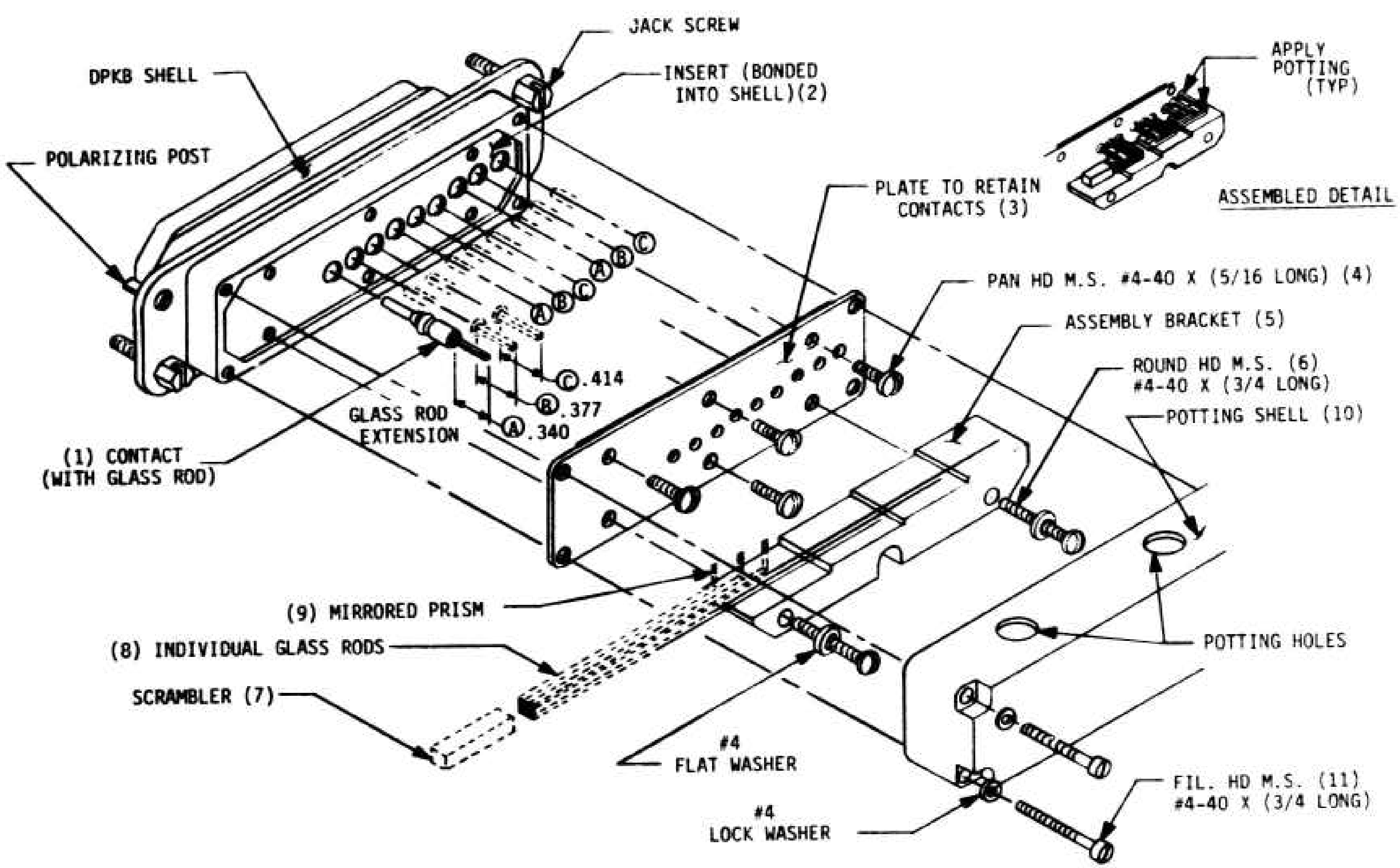


Figure 30: Radial Coupler in DPK Connector

The nine square side arms form a 3 by 3 square array. This interfaces with the square scrambler rod to form an interface with no void space as with round rods or fibers. The only packing fraction loss at this interface is the area loss due to cladding on the side arms and the area loss due to mechanical misalignment.

To form an interface with each fiber bundle on an individual basis each side arm makes a 90° bend. This 90° turn is accomplished with a mirrored 45° prism. Each turn is spaced laterally to allow for the desired clearance between adjacent side arms.

ITT Cannon Electric Division modified their DPK connector to house this radial coupler design. Figure 30 shows the assembly drawing of this connector with the radial coupler piece parts. Housing the radial coupler in a multicontact connector offers several advantages over other designs. These are:

- Reduction in physical size
- Easily accessible and pluggable interfaces
- Proven reliable housing
- Minimum retooling for production

Figure 31 shows the rear view of the radial coupler with the potting shell removed. This view shows the exposed side arms, scrambler and prisms before the final step of assembly is completed. After the back shell is added these glass parts are potted to provide good protection from physical shock as well as provide a good environmental seal.

Figure 32 shows the front view of the radial coupler with the spacing of each side arm. The side arms are recessed in the connector insert as this provides accurate alignment to the fiber bundle ferrules. This insert is removable for cleaning of the optical surfaces, a requirement in pluggable optical interfaces.

The square side-arm radial coupldер was evaluated by introducing a constant optical input successively into each of the nine arms of

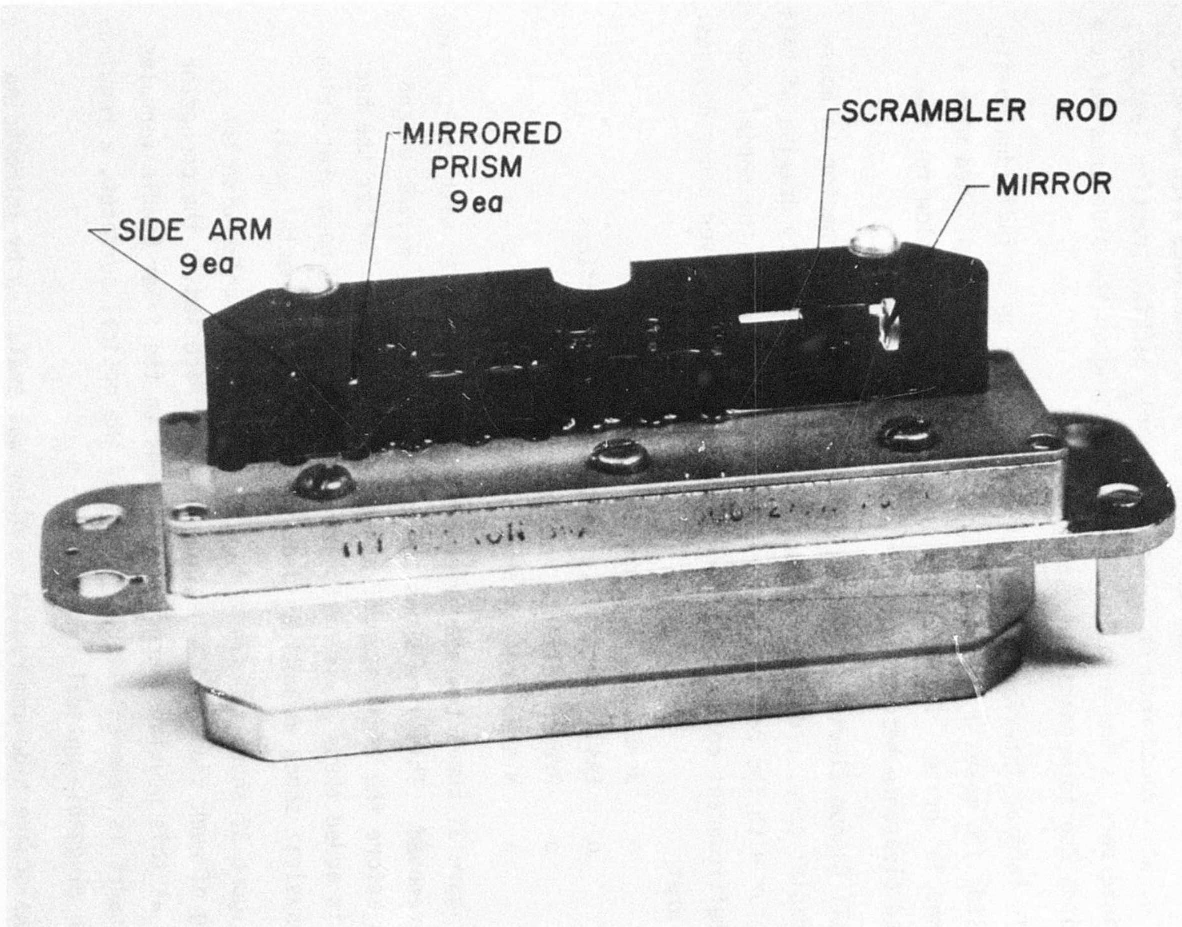


Figure 31: Radial Coupler (Rear View)

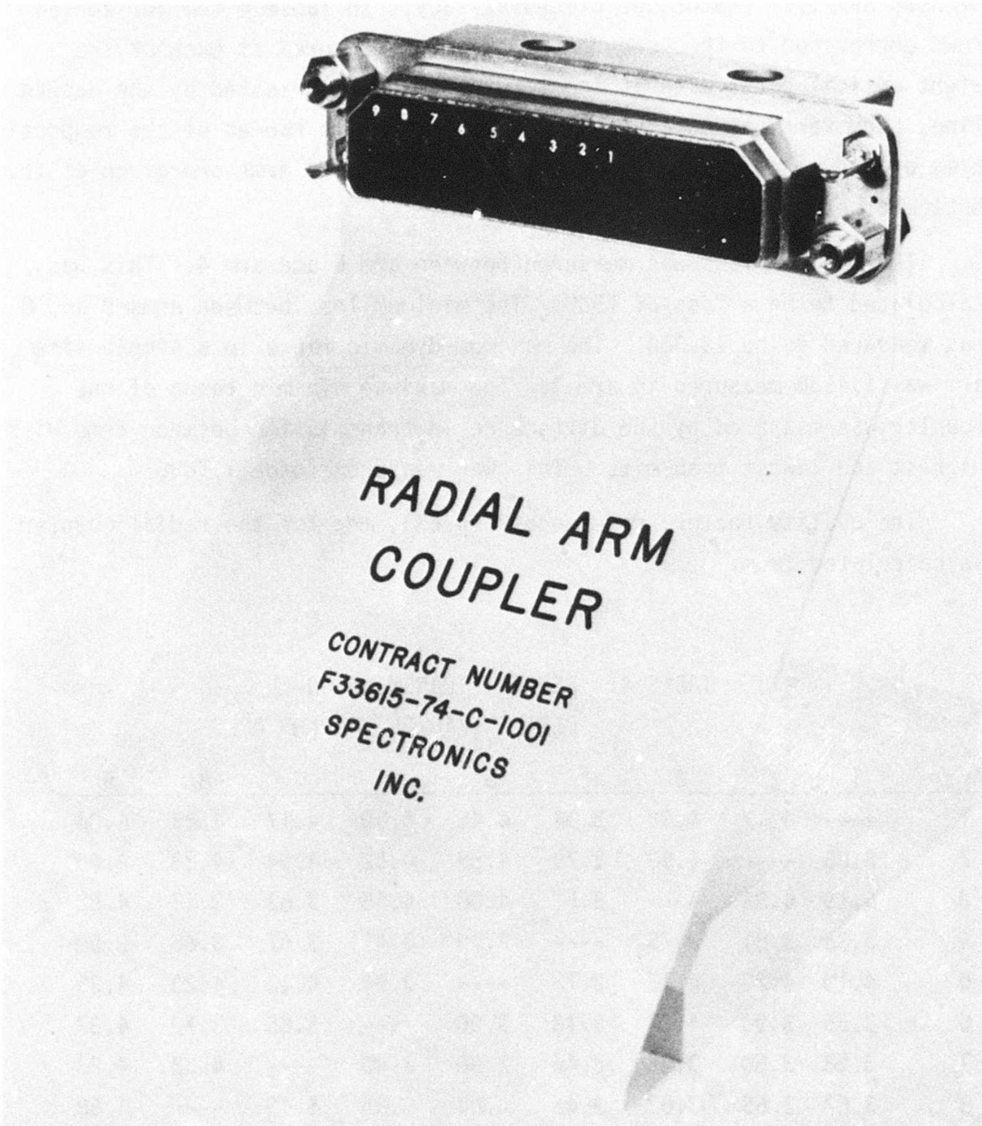


Figure 32: Radial Coupler (Front View)

the coupler and measuring the output of each of the remaining eight arms. The input was introduced into the coupler using the detector portion of the bifurcated Valtec fiber bundle excited at the opposite end with an SPX 1775 LED. Signals out of the coupler were measured with an SPX 1777 photodiode biased at -30V. In Table 4 the horizontal rows correspond to the percent transmission measured at each of the eight optical ports with an input into the port indicated by the dashed line. The vertical columns represent the dynamic ranges of the respective arms of the coupler, and the D_{R*}'s for each of the arms are given at the bottom of each column.

The maximum loss was measured between arm 6 and arm 4. This was calculated to be a loss of 15dB. The minimum loss between arms 9 and 8 was measured to be 13.3dB. The maximum dynamic range in a single side arm was 1.45dB measured in arm 3. The maximum dynamic range of the coupler was measured by the difference in transmission between arms with highest and lowest transmits. This was measured to be 1.7dB.

The quality factor, reference 2 (p 57), m*, for the radial coupler is calculated from:

$$m_* = T_* N$$

TABLE 4. PERCENT TRANSMISSION BETWEEN RADIAL COUPLER ARMS

Arm	1	2	3	4	5	6	7	8	9
1	----	4.17	4.38	3.94	4.42	4.00	4.17	4.23	4.06
2	3.85	----	4.58	3.79	4.58	4.52	4.04	4.23	4.46
3	4.19	4.38	----	3.5	4.08	4.46	3.62	3.83	4.62
4	3.85	3.81	3.75	----	3.79	3.42	3.67	3.65	3.60
5	4.19	4.23	4.13	3.75	----	3.94	4.13	4.23	4.33
6	3.65	3.90	4.27	3.13	3.90	----	3.65	3.79	4.37
7	3.58	3.50	3.27	3.46	3.90	3.46	----	4.52	4.23
8	3.67	3.65	3.63	3.46	4.04	3.85	4.40	----	4.58
9	3.69	4.00	4.04	3.56	4.52	4.60	4.42	4.73	----
D_R(dB)	.60	.98	1.46	1.00	.82	1.28	.88	1.12	1.08

where:

$T_\star$ is the average transmission of the side arms

N is the total number of side arms

$m_\star = (.04)\ 9 = .36\ (-4.4dB)$

b. Fiber Optics Bundle

The fiber bundles used on the data bus are the plastic clad fused silica fiber manufactured by Valtec. Specifications for this fiber bundle are given in Table 5.

TABLE 5. SPECIFICATIONS FOR VALTEC FIBER BUNDLES

Number of fibers	37
Fiber diameter	5.0 mils ± 10%
Core diameter	4.0 mils ± 10%
Jacket	63 Durometer Hytrel .110"OD
Numerical Aperture	.3
Attenuation	100dB/KM @ 907nm

The actual fiber bundles received from Valtec did not meet the above specifications. The parameters for the received fiber bundles are shown in Table 6.

TABLE 6. MEASURED PARAMETERS OF VALTEC FIBER BUNDLES

Number of fibers	42
Average fiber diameter	5.6 mils
Average core diameter	4.6 mils
Jacket	.140"OD
Attenuation	127dB/KM @ 907nm

The deficiencies in the Valtec fiber bundles were determined not to be critical; so to avoid delay in delivery of the contract hardware, the fiber bundles were used in the system. To overcome the deficiencies only

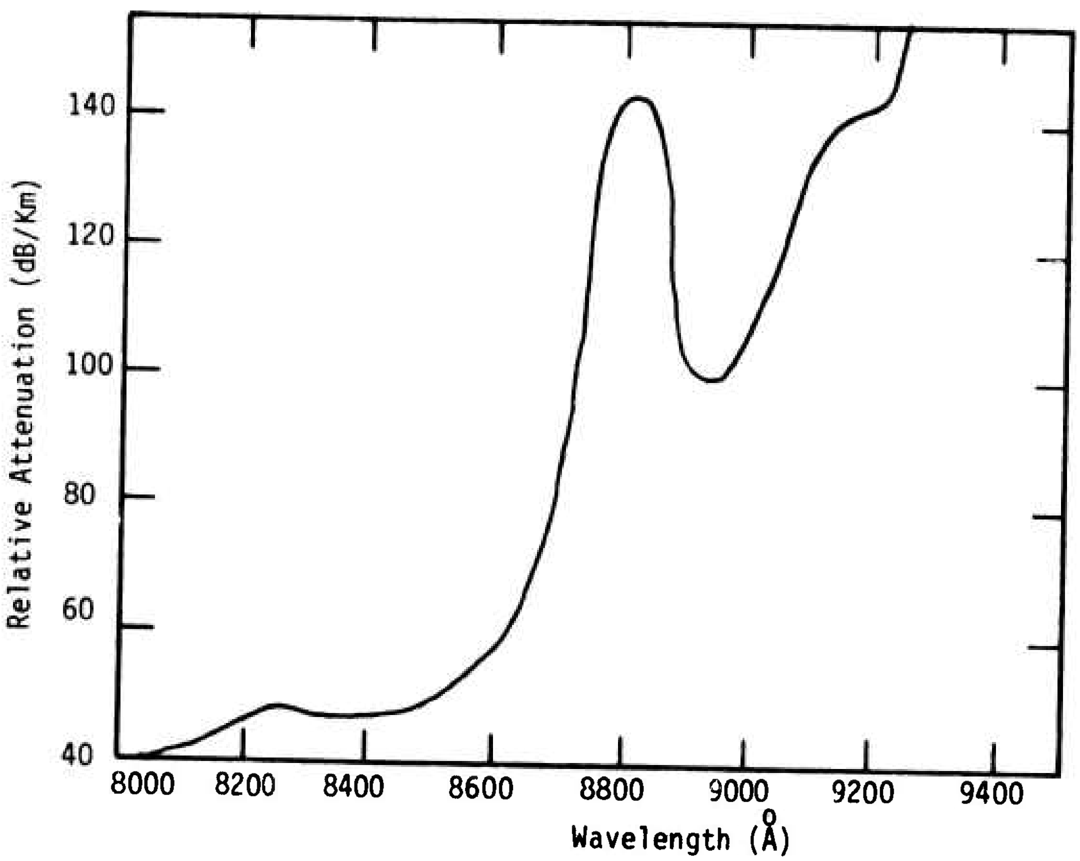


Figure 33: Attenuation of Valtec Fibers vs λ

37 of the 42 fibers in the bundle were used; also the terminating ferrules were modified to accept the oversized fibers and the oversized jacket.

A spectral response was run on the Valtec fiber and is shown in figure 33. The attenuation between 8000Å and 8500Å is less than 50dB/KM where the fiber is specified by Valtec.

A single bundle of the Valtec fiber is used for each arm of the radial data bus. This bundle is bifurcated on the station end with 19 of the 37 fibers going to the detector and 18 going to the LED. This is effectively a small diameter fiber bundle. The smaller low loss bundles offer advantages over both the larger low loss and high loss fiber. Even though the coupling efficiency is less in the small low loss fibers the total attenuation in 100 ft of fiber is less than in the high loss. Advantages over the large low loss fiber are:

- lower cost than larger low loss bundles
- small size bundles permits use of smaller size passive coupler
- high coupling efficiencies to the detector.

The only performance area where a large low loss fiber is superior to the smaller bundle is in coupling to a LED. This can be partially overcome by placing the fibers in an area of highest radiant intensity, if the LED does not have a uniform power distribution.

c. FO Cable/Coupler Interface

The Cannon DPK connector was used as the pluggable interface between the radial coupler and the fiber bundles as shown in figure 34. Each of the fiber optics termination ferrules is a removable contact for the connector. The contact floats in the connector as the coupler half provides the alignment for each contact. The contacts are "O" ring loaded to provide a means to take up axial tolerances in mating of the two connector halves.

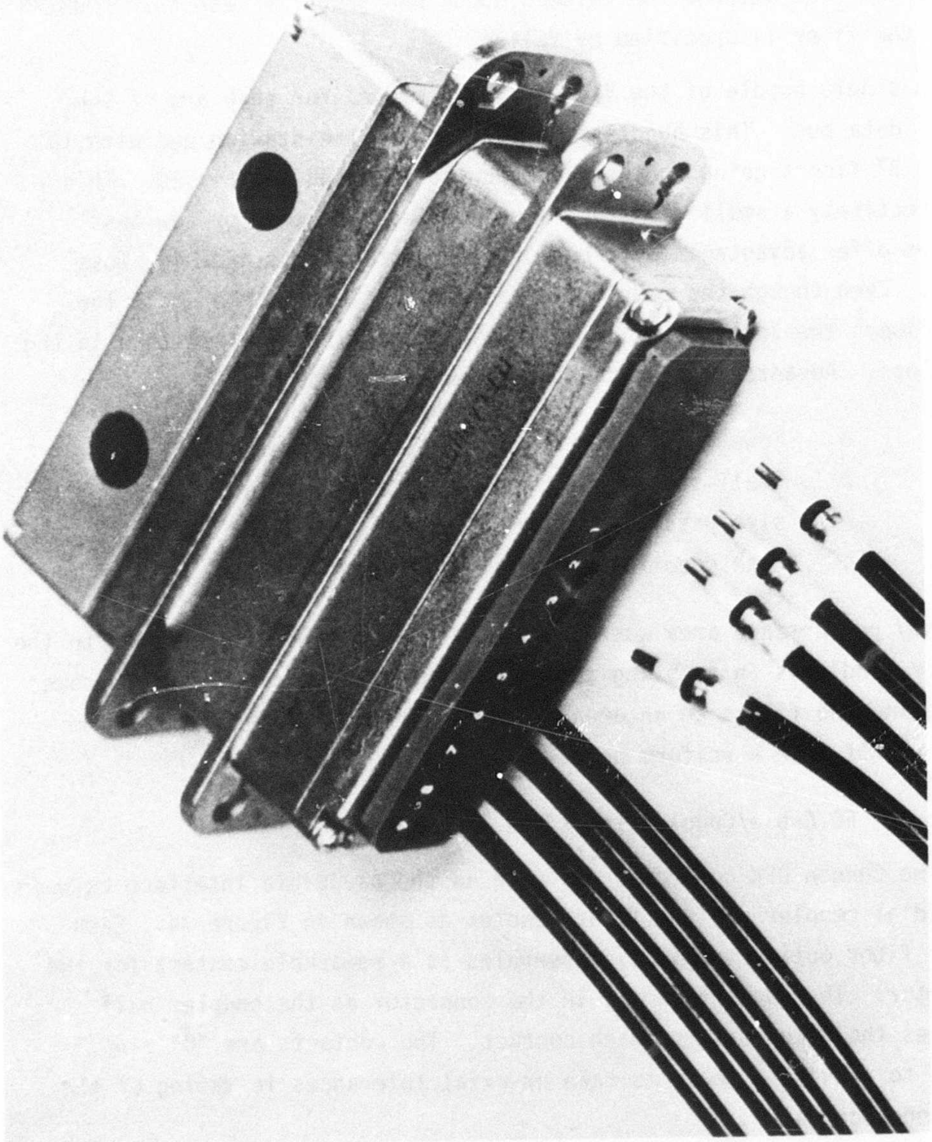


Figure 34: Radial Coupler/FO Cable Interface

The fibers are terminated in a circular pattern even though the side arms are square. This was done so that no keying would be required in inserting the ferrules in the connector. This makes the alignment problems less critical. The extra loss encountered in doing this is the difference in area of the inscribed circle which calculates to be $\pi/4$ or 1dB.

The only problem encountered in matching the square rods and the round fiber termination was in the fact that the fibers were larger than originally specified. The individual Valtec fibers were supposed to be .005 in giving a hex diagonal of 37 mils. To match this, 37 mil square side arms were ordered. However when the Valtec fibers were received, the fibers were .0056 inches in diameter giving a hex diagonal of 39 mils. These fibers will overlap the square side arms adding slightly to the coupling loss.

d. FO Cable/LED Interface

As shown in figure 35, the light output pattern of an SPX 1775 is not uniform across a diameter. The peak output of the LED is contained in an annular ring 37 mils in diameter and 10 mils wide. Thus, for a fiber bundle containing an insufficient number of fibers to fill the entire 45 mil aperture, the best coupling can be achieved by placing as many of the fibers as possible in a 37 mil diameter annular ring.

Figure 35 represents the instantaneous power density as a function of distance across a diameter of the LED. To obtain the total power out of the LED, the curve must be rotated about r=0 and integrated to obtain the volume under the curve of figure 36. To calculate the total power output in a 0.24NA, it is assumed that the cross section sampled is representative of all the cross sections through the center of the LED. This curve of instantaneous power density, Z(r), is multiplied by the radius, r, at each point and integrated in cylindrical coordinates to give total power in a .24NA.

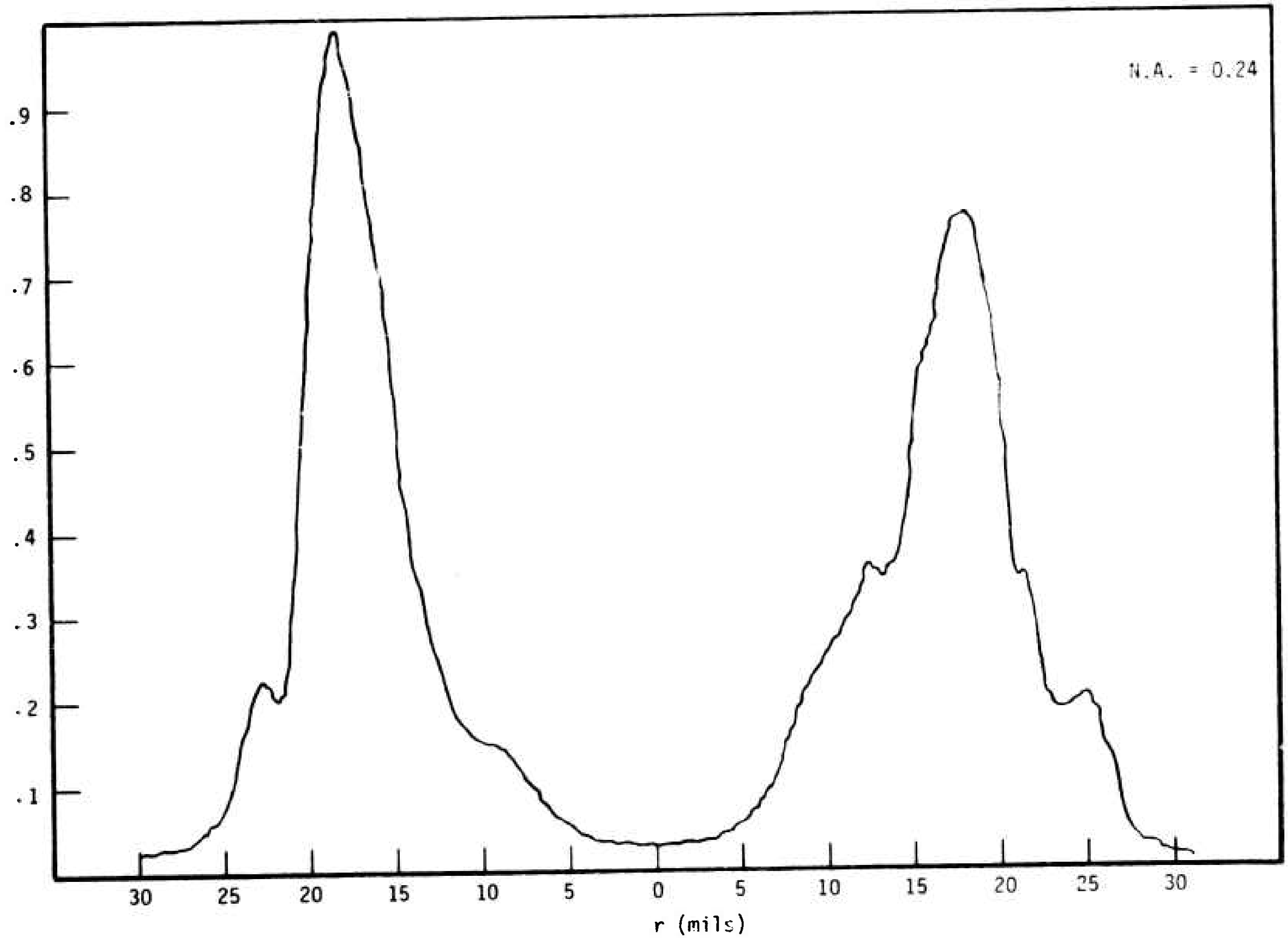


Figure 35: LED Output Intensity vs Radius

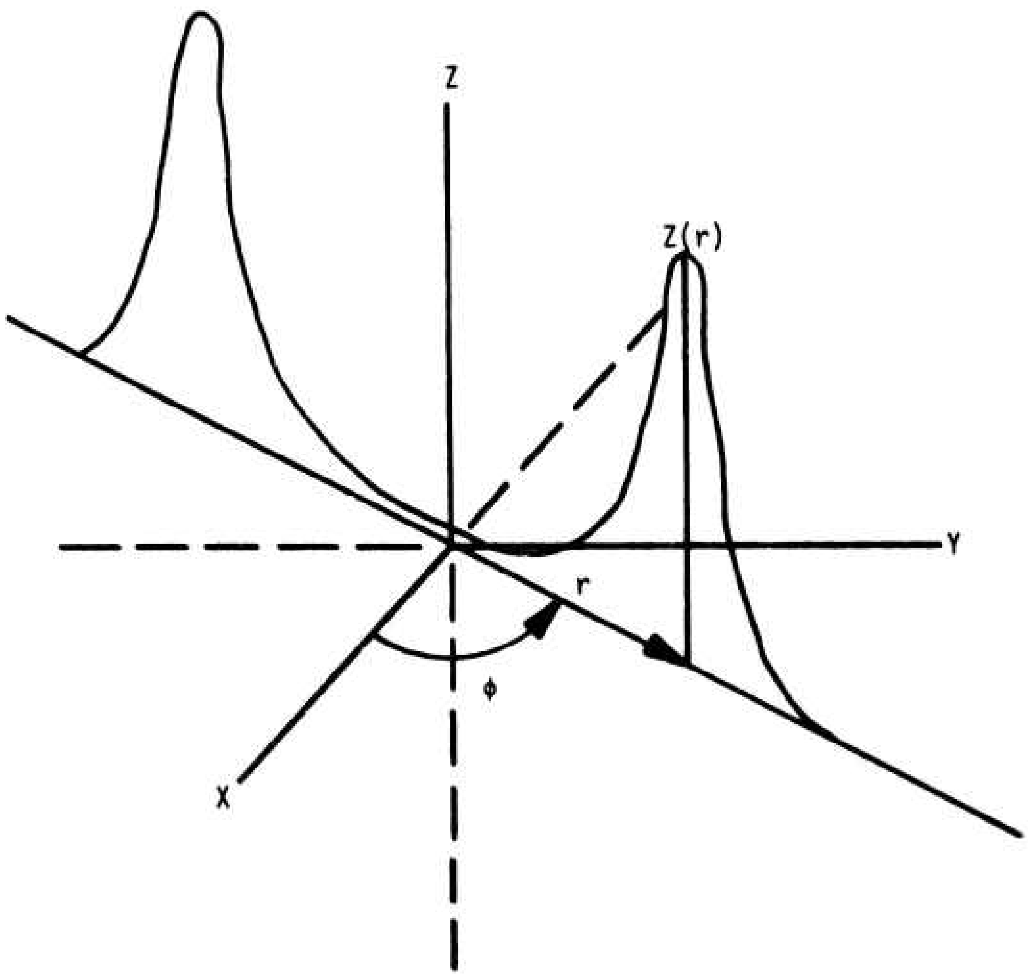


Figure 36: Radiant Output of SPX 1775
Versus Radial Distance

SPX 1775 -#B1

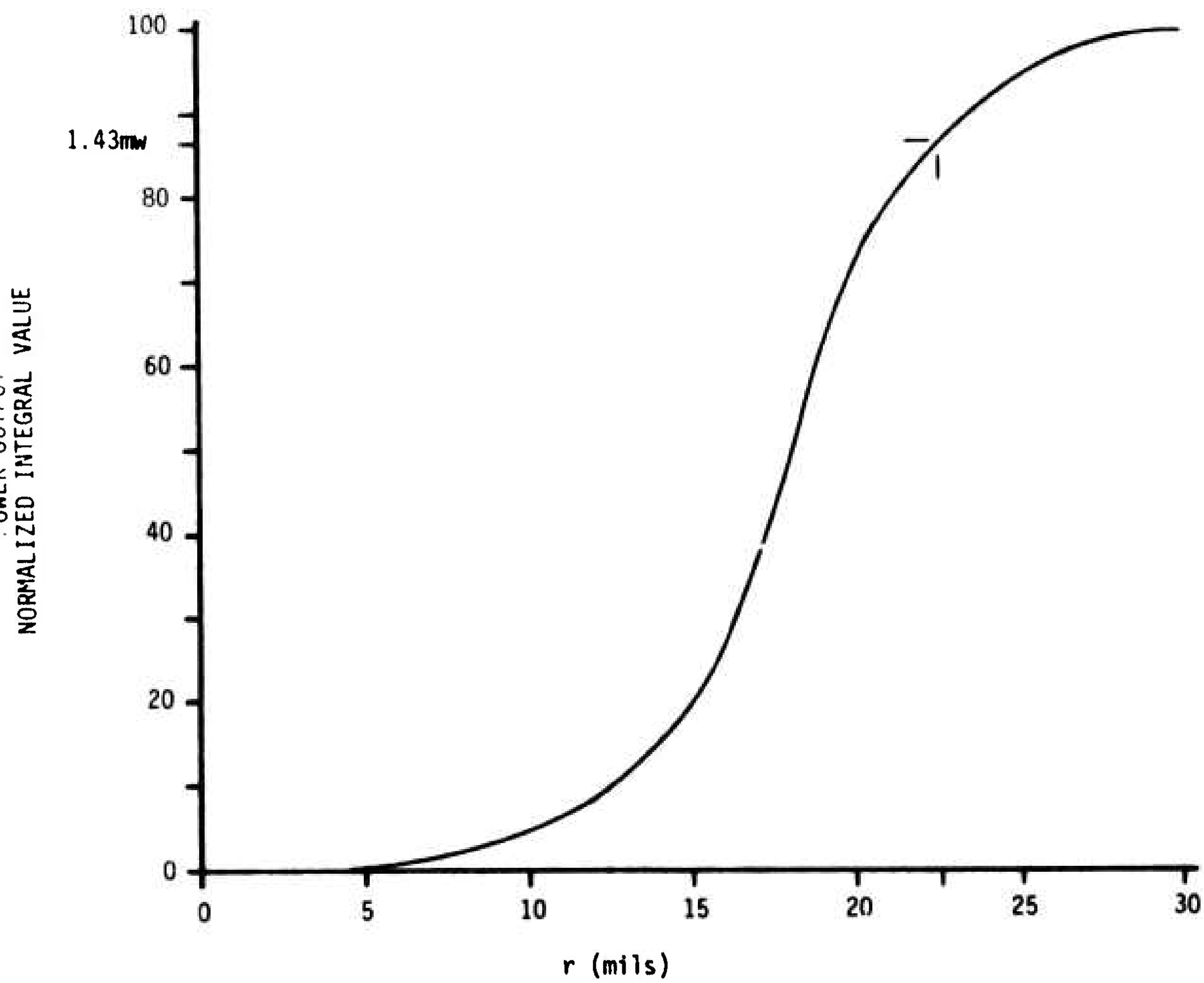


Figure 37 : Percent of Total Light Output Versus Radial Distance for A Numerical Aperture of 0.24

$$P_T = \int_0^{2\pi} \int_0^{r_{max}} \int_0^{Z(r)} r dr d\phi dz$$

$$= 2\pi \int_0^{r_{max}} r dr \left[\int_0^{Z(r)} dZ \right] \quad (8)$$

$$P_T = 2\pi \int_0^{r_{max}} rZ(r) \; dr \quad (9)$$

For each value of the radius, r, there are two values of Z(r), one on each side of the center. These were averaged and this average value was then used for evaluating the integral. Equation 9 was numerically integrated from r=0 to r=30 mils, and the normalized value of the integral is shown in figure 36 as a function of radial distance. An independent measurement of total power through a 45 mil diameter aperture into a 0.24NA was used to calibrate the r=22.5 mil point in figure 37.

The maximum number of fibers, N_{max}, of diameter d, which can be placed in an annular ring of average diameter, D, is

$$N_{max} = \frac{180}{\mathrm{Sin}^{-1}\left(\frac{d}{D}\right)} \quad (10)$$

For the Valtec fibers d = 5.6 mils and from figure 34 D = 37 mils. For Valtec fibers the maximum number of fibers that can be placed in a 37 mil diameter ring is

$$N_{max} = \frac{180}{\mathrm{Sin}^{-1}\left[\frac{5.6}{(37)}\right]} = 20.7 \quad (11)$$

Therefore 18 of the 37 fibers will fit in the 37 mil annular ring with 19 left for the detector interface.

The outside and inside radius of the ring of fibers are:

$$r_o = \frac{D + d}{2} = \frac{37 + 5.6}{2} = 21.3 \text{ mils} \quad (12)$$

$$r_i = \frac{D - d}{2} = \frac{37 - 5.6}{2} = 15.7 \text{ mils} \quad (13)$$

To calculate the percent of total power in a .24NA through the annular ring, the percent power through the smaller radius is subtracted from the percent of power through the large radius. From figure 37 where:

$$P_{(r_i)} = 24\%$$

$$P_{(r_o)} = 81\%$$

$$P_{(r_o)} - P_{(r_i)} = 81 - 24 = 57\% \quad (14)$$

Therefore 57% of the total LED power in a .24NA passes tnrough the annular ring described by r_o and r_i. The packing fraction of this annular ring is calculated by the ratio of fiber core area to ring area or:

$$P = \frac{N\pi r^2}{\pi r_o^2 - \pi r_i^2} = \frac{Nr^2}{r_o^2 - r_i^2} \quad (15)$$

$$P = \frac{18\ (2.3)^2}{21.3^2 - 15.7^2} = .46 \quad (16)$$

The percent total power coupled into the fiber bundle is then calculated from the ratio of the total power and total power in a .24NA plus the front surface reflection.

$$\%P_T = (57)(.46)(1-R)\frac{P_N}{P_T} = \qquad (17)$$

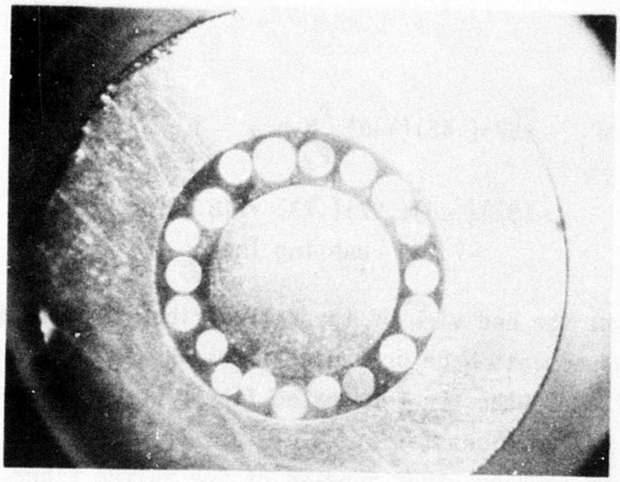
$$(57)(.46)(.97)(.73) = 18.6\% \text{ or}$$
$$-7.3\text{dB coupling loss}$$

Figure 38 shows the end view of the Valtec fiber terminated in the ring fashion. Measurements made on these fibers showed an average coupling loss of 13.7dB when the terminated fibers were received from ITT Cannon. This was an excess of 5.8dB of loss from the above calculated value. Measurements made on other bundles of the Valtec fiber, some terminated by Spectronics, Inc. and some by Valtec, Inc. also showed this excess loss in the range of 5 to 6dB. Upon further inspection of the polished fiber, it appeared the fused silica was not sufficiently polished by the standard process used on the other glass clad fibers. After repolishing the termination with diamond paste down to 3 microns, the loss in the ring termination was reduced to 10.5dB. This is still in excess of 3dB from the calculated value and is believed to still be caused in the polishing technique used, as this characteristic is only typical of the plastic clad fused silica fibers. All previous measurements made on glass clad fibers have agreed with calculated results. Further investigation is needed to determine the causes of the excess losses in the plastic clad fused silica fiber terminations.

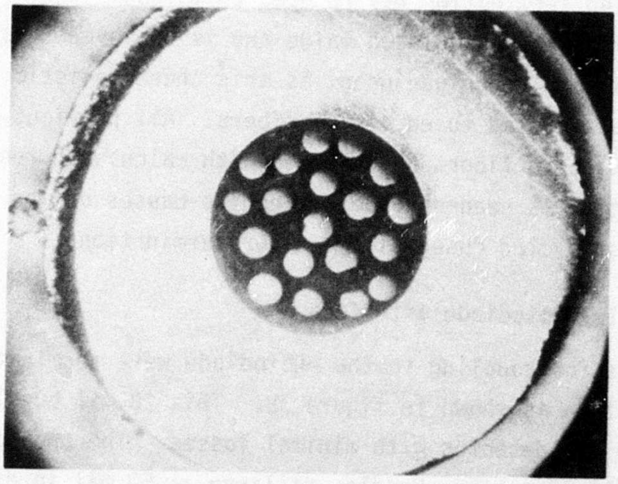
e. FO Cable/Photodiode Interface

The 19 fibers for coupling to the photodiode were terminated in a 28 mil hexagonal pattern as shown in figure 38. This 28 mil bundle interfaces with the 50 mil detector with minimal losses. The photodiode was designed for coupling to fiber bundles as large as 50 mil in diameter, so the only losses in this interface are due to front surface reflection.

The connector for mounting the fiber bundles is shown in figure 39. This connector houses the LED fiber termination as well as the photodiode termination. This connector mates with the connector of figure 21.



RING TERMINATION FOR LED INTERFACE



CIRCULAR TERMINATION FOR PHOTODIODE INTERFACE

Figure 38: Fiber Bundle Terminations

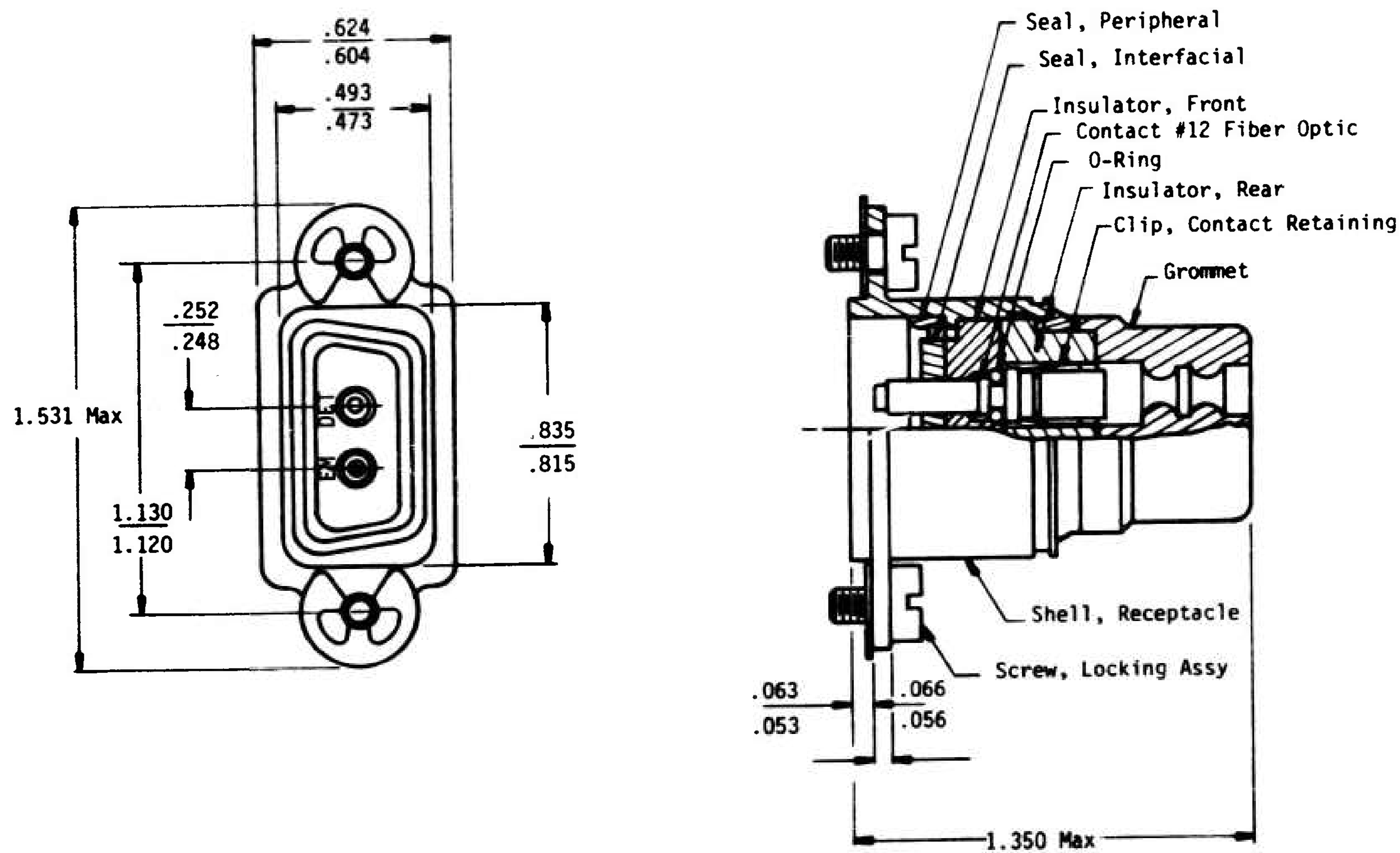


FIGURE 39: CONNECTOR HOUSING FOR FIBER BUNDLES

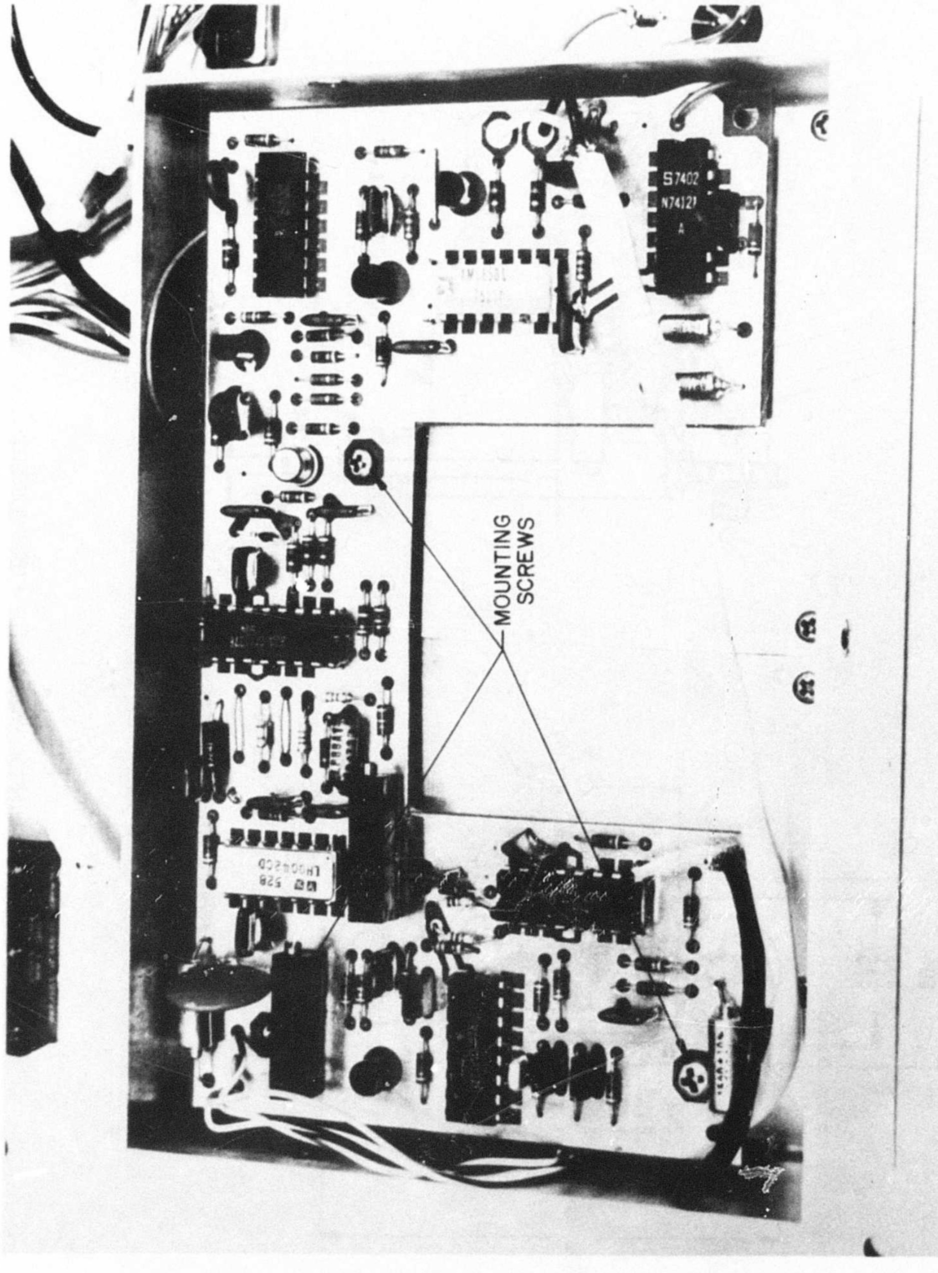


Figure 40: Postamp and Signal Conditioning Mounting

3. Data Processing

The MTUs and CMTUs were constructed as typical bench-mounted commercial instruments. All have tiltstands, carrying handles and employ forced air cooling.

To implement construction, the MTUs and CMTU were broken down into 7 separate functional subsystems. This provided for ease of construction as each section could be built on separate PC boards and checked separately. Also the similarity in the MTU and CMTU function would allow for four of the MTU subsystems to be used in the CMTU, with two of the remaining three requiring minor design modification to implement the CMTU function. The seven subsystems are:

- o Receiver and signal conditioning
- o Sync detection
- o Data selection
- o Memory
- o Output
- o Transmitter
- o Timing and Control

The receiver, signal conditioning and transmitter were described in Section III-2. These sections were constructed on separate PC boards that mounted to the front panel of either the MTU and CMTU as is shown in figures 27, 40 and 41.

The Sync detection subsystem was constructed on two pluggable PC boards as this section contained the 100MHz clock, and uses ECL logic to implement the sync detection. The remaining four subsystems were constructed on pluggable wire wrap circuit boards, with the same outline dimension as the sync detection board. These six boards were housed in a card cage occupying one half of the instrument case. These circuit boards are accessible through removal of the rear panel of the cases

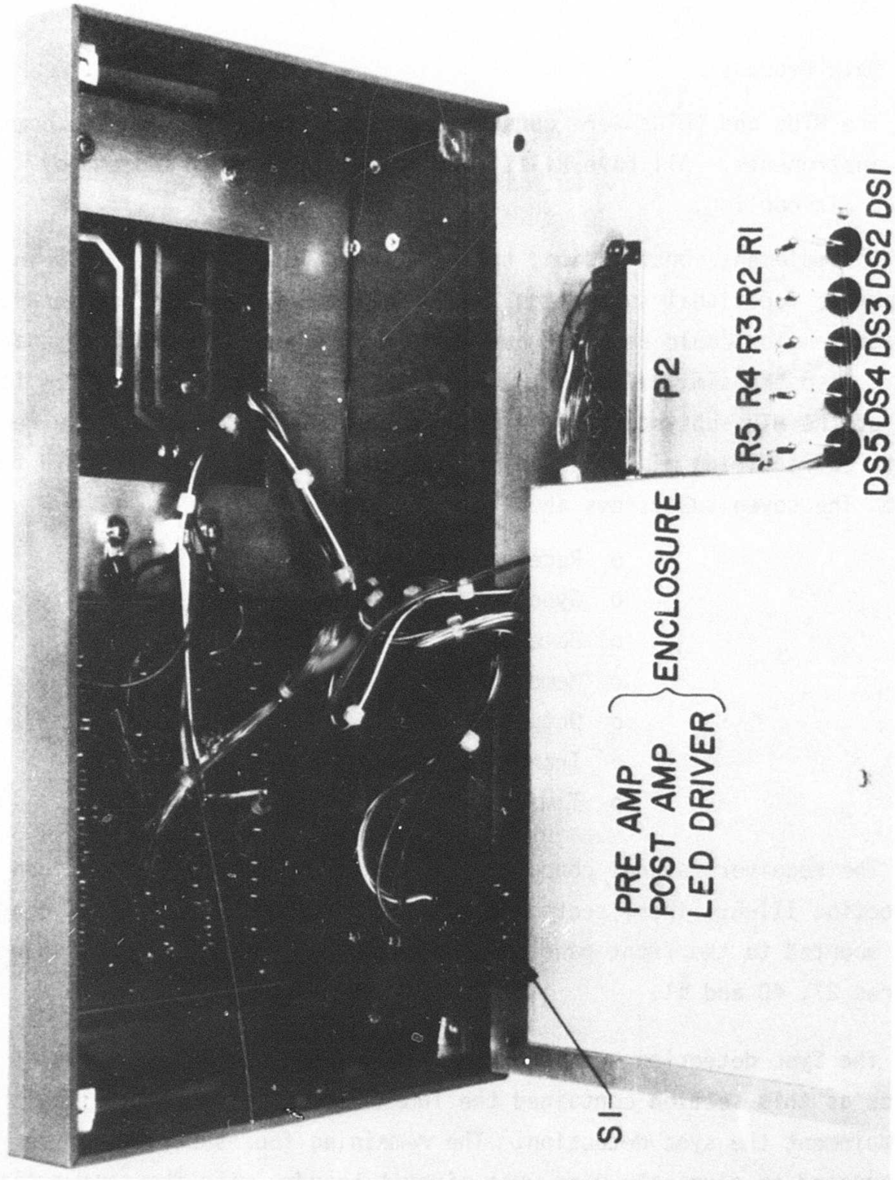


Figure 41: Front Panel Mounting

(figure 42). The remaining half of the instrument case houses the modular power supplies and the blower (figure 43).

a. MTU

i. Sync Detection

The problem in sync detection is the detection of one of two types of 300ns sync pulses on the data bus. The first type, called a positive sync, is a 150ns logical "1" state followed by a 150ns logical "0" state. The second type, called a negative sync is a 150ns logical "0" state, followed by a 150ns logical "1" state. Figure 44 shows a block diagram of the sync detection circuit.

The technique used to detect sync and accurately clock the incoming data or command, is to detect the transition in the sync pulse. This is done by sampling the data bus signal at a rate 10 times faster than the data rate (100MHz). This sampled data is stored in a register where it can be monitored. At the 100MHz sampling rate, a positive sync will ideally be represented by 15 logical "1's" followed by 15 logical "0's". However, to allow for distortion in the received signal, due to finite rise times in the transmitter and limited bandwidth in the receiver, the circuit allows for a positive sync to be represented by twelve "1's" followed by twelve "o's". The register described above is a 16 bit shift register. Fourteen of the bits are continuously monitored and in the event that 12 of the bits are "1's", a counter is set. When the all "1's" condition is no longer met, the counter is started and reset at a count of 15. If an all "0's" condition has been met before the count out cycle, it indicates that a positive sync has been detected and that the end of the count out cycle indicates the end of the sync pulse.

The negative sync is detected the same as the positive with "1's" and "0's" conditions reversed.

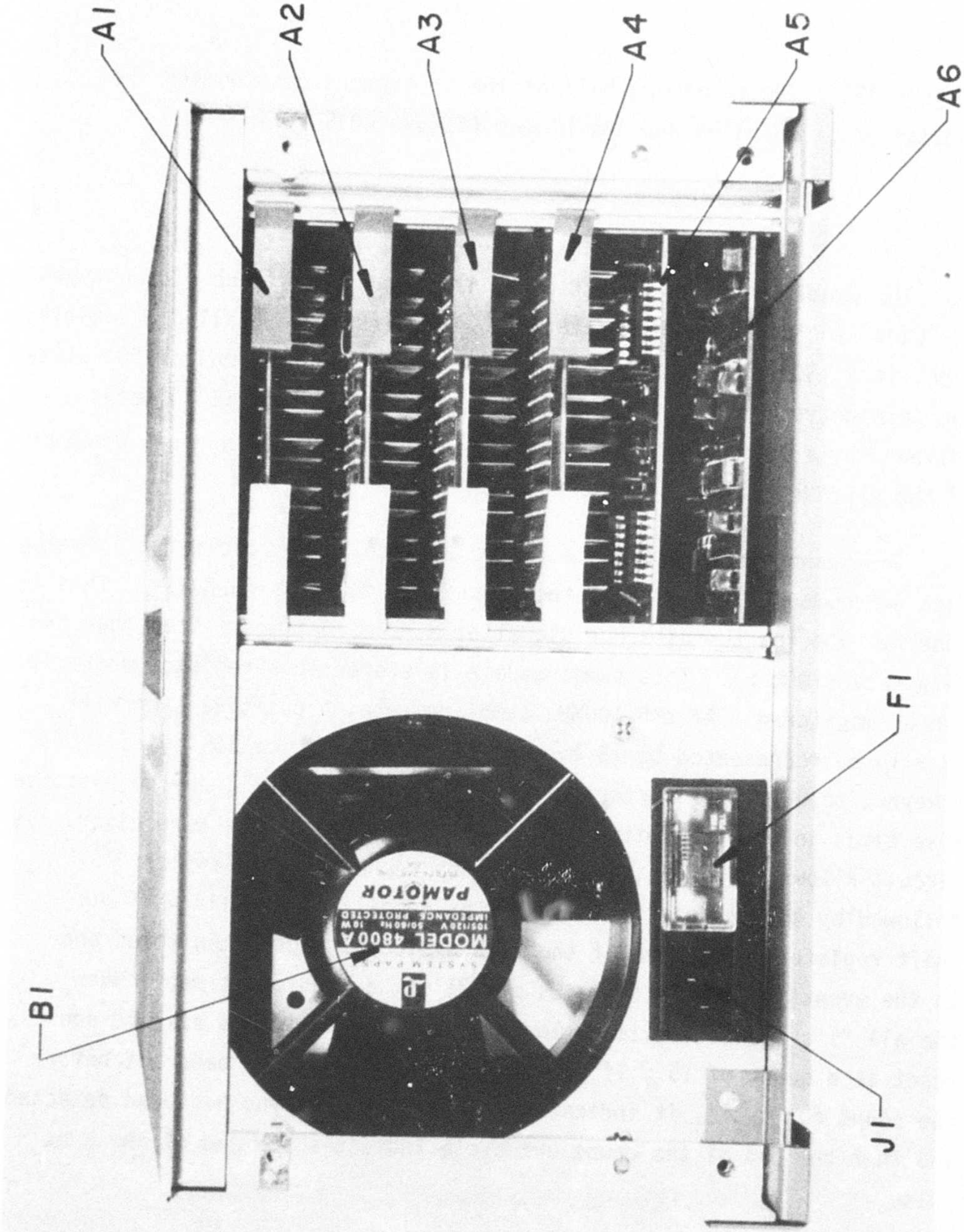


Figure 42: Rear of MTU (Cover Removed)

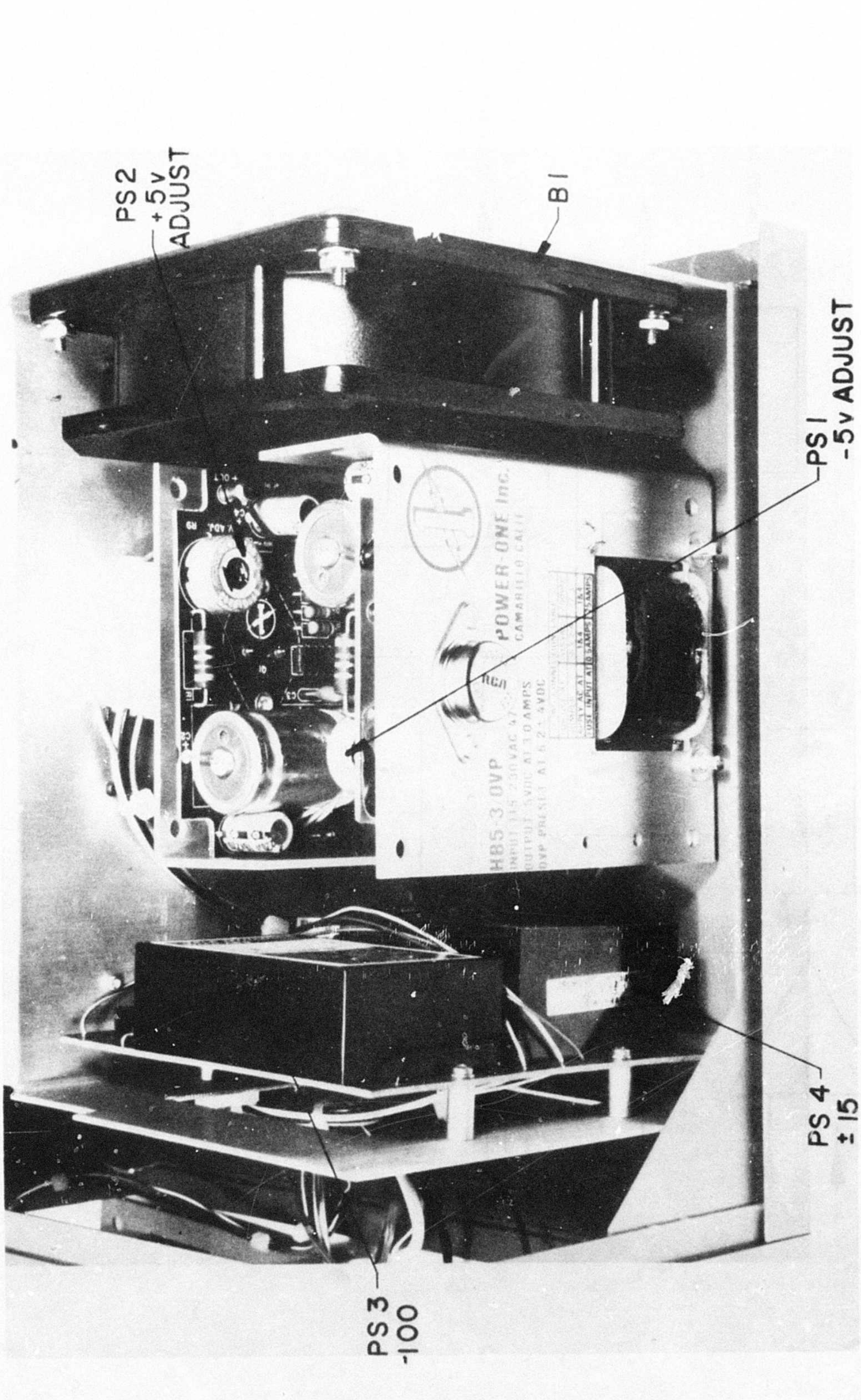


Figure 43: MTU (Cover Removed)

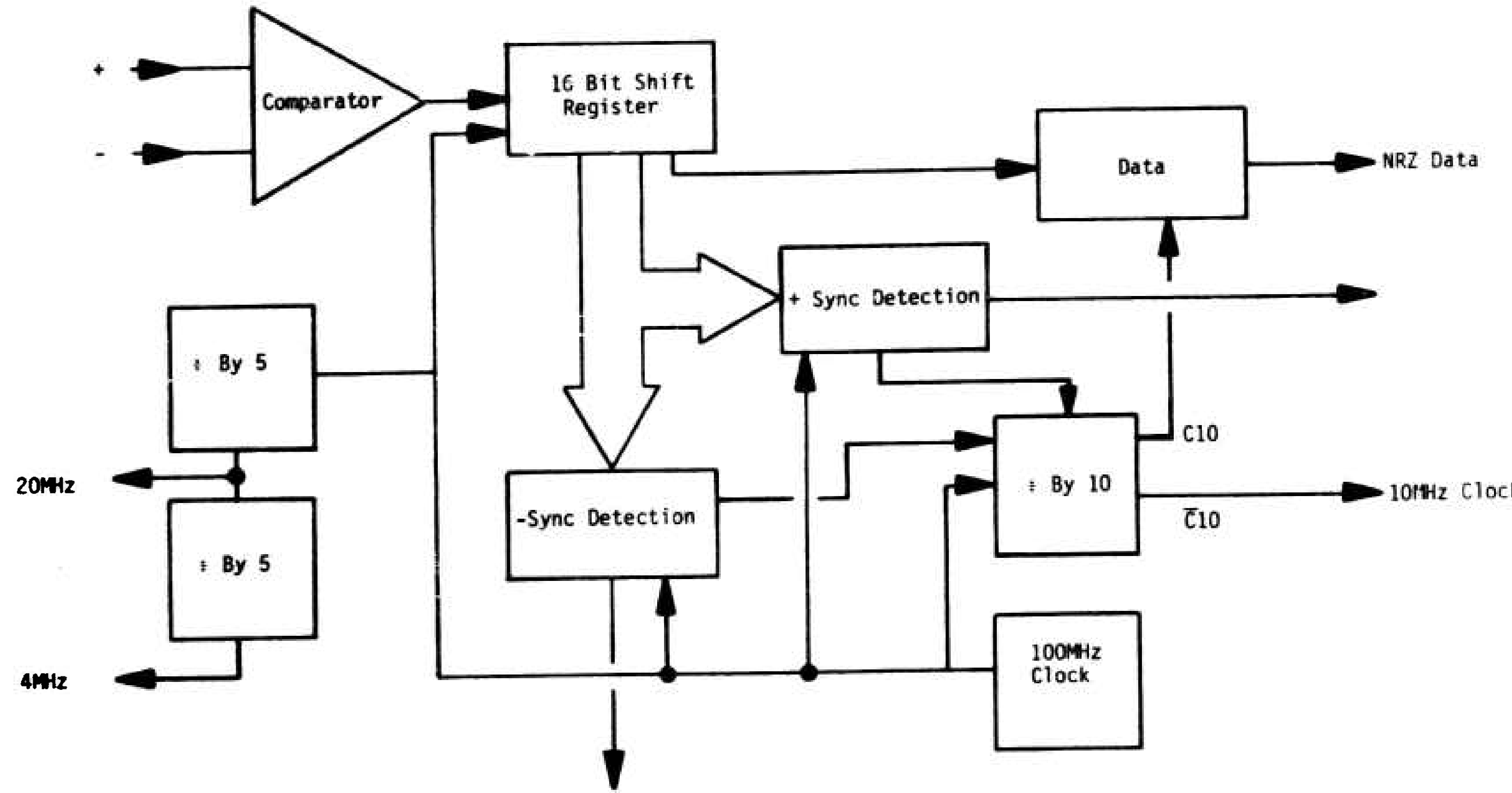


Figure 44: Sync Detection

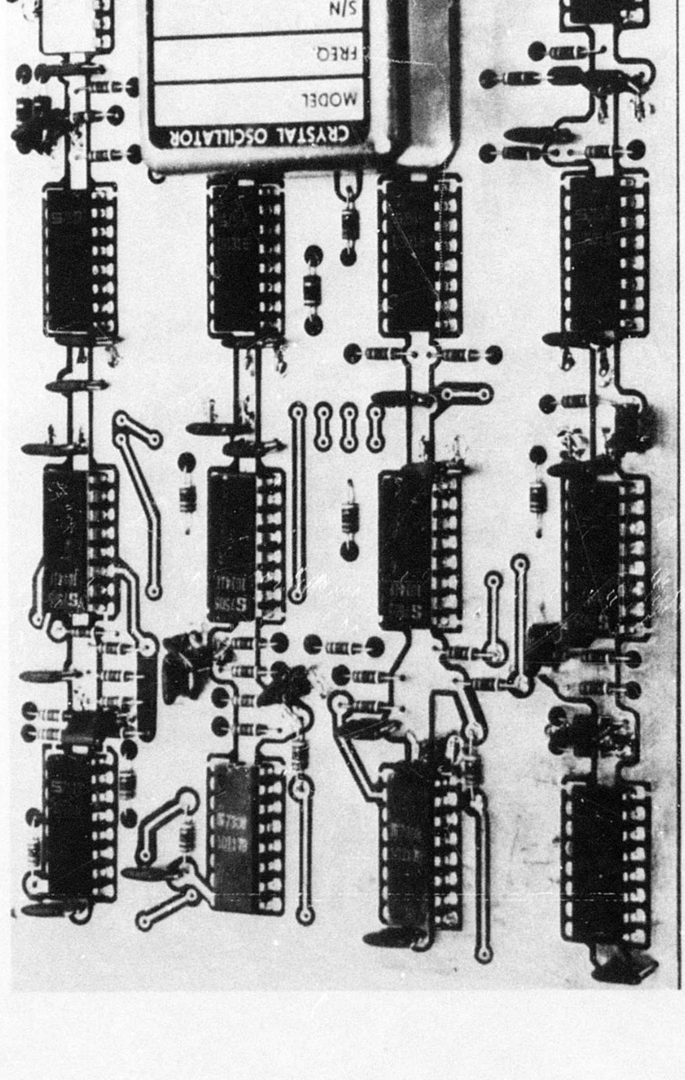


Figure 45: Sync Detection PCB

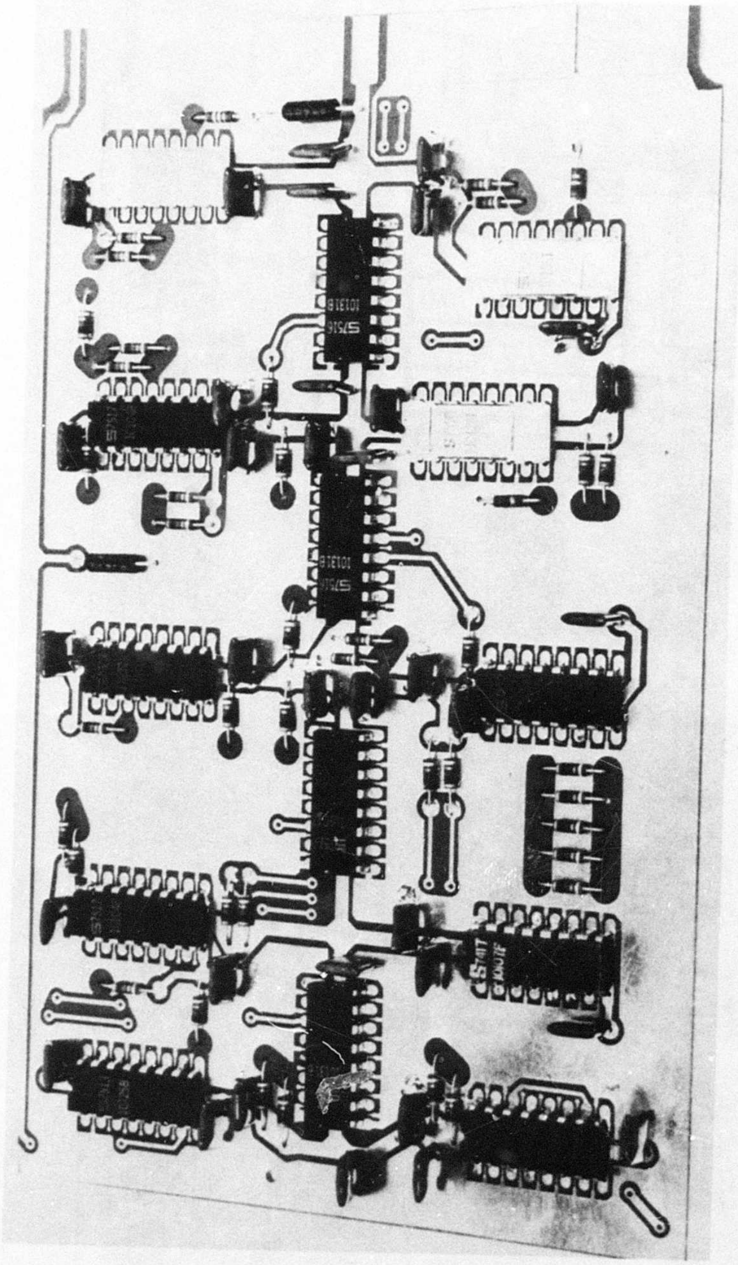


Figure 46: Clock, ECL/TTL Translator PCB

The transition at the center of the sync pulse is used as a reference as the beginning or end of a sync pulse may not have a transition. The 100MHz sampling rate gives an indication of ± 10% as to where the sync transition occurred. When a sync signal is detected, a 10MHz clock is rephased to strobe the incoming data to convert it from Manchester to NRZ.

The Sync detection circuit also provides the 4MHz clock used by the MTU and SSIU for data control. Other clocks provided are a 10MHz clock for data input and a 20MHz clock for use in the output section.

The 100MHz master clock used in the sync detection requires the use of high frequency techniques in construction of the two PC boards shown in figures 45 and 46. ECL logic was used in this section as it gives the best high frequency performance. The interfaces between this section and the rest of the MTU logic function requires ECL to TTL and TTL to ECL translators.

ii. Data Selection

The Data selection provides the data routing control for the MTU as is shown in the block diagram of figure 47. The serial data stream is received from the sync section and converted to a 17 bit parallel word. The word is then checked for odd parity. Command words are stored in the command latch and routed to the SSIU at the appropriate time. Data words are temporarily stored in the data latch until they are routed to the memory for storage. Data words received from the SSIU are also routed through the data selection to the memory.

iii. Memory

The Memory section contains a 32 word by 16 bit memory, read/write control logic and read/write counter for memory address control. Figure 48 shows a block diagram of the memory function. Data words are received from the data bus or SSIU through the data select and are transmitted to the data bus through the output section.

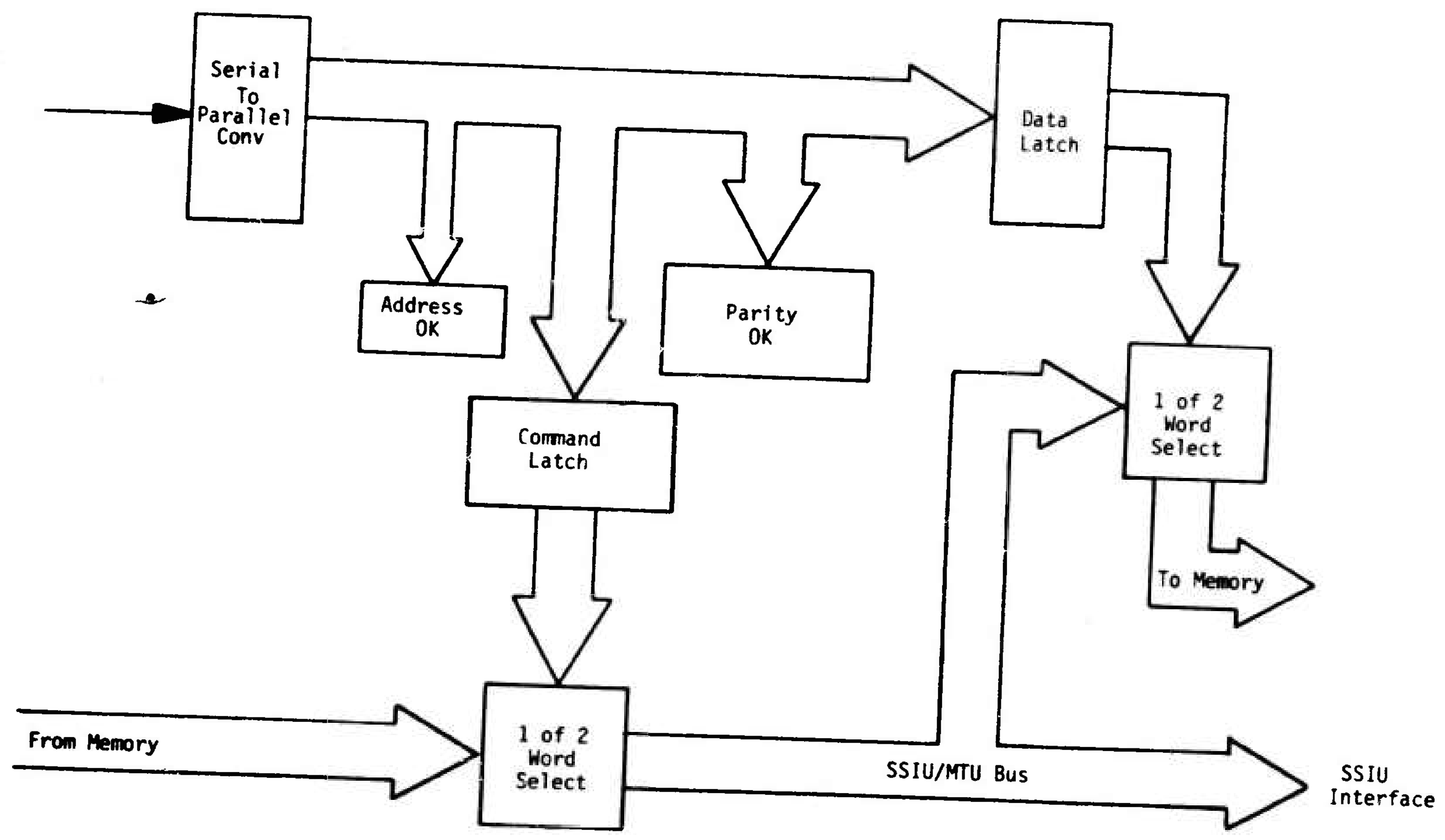


Figure 47: Data Selection

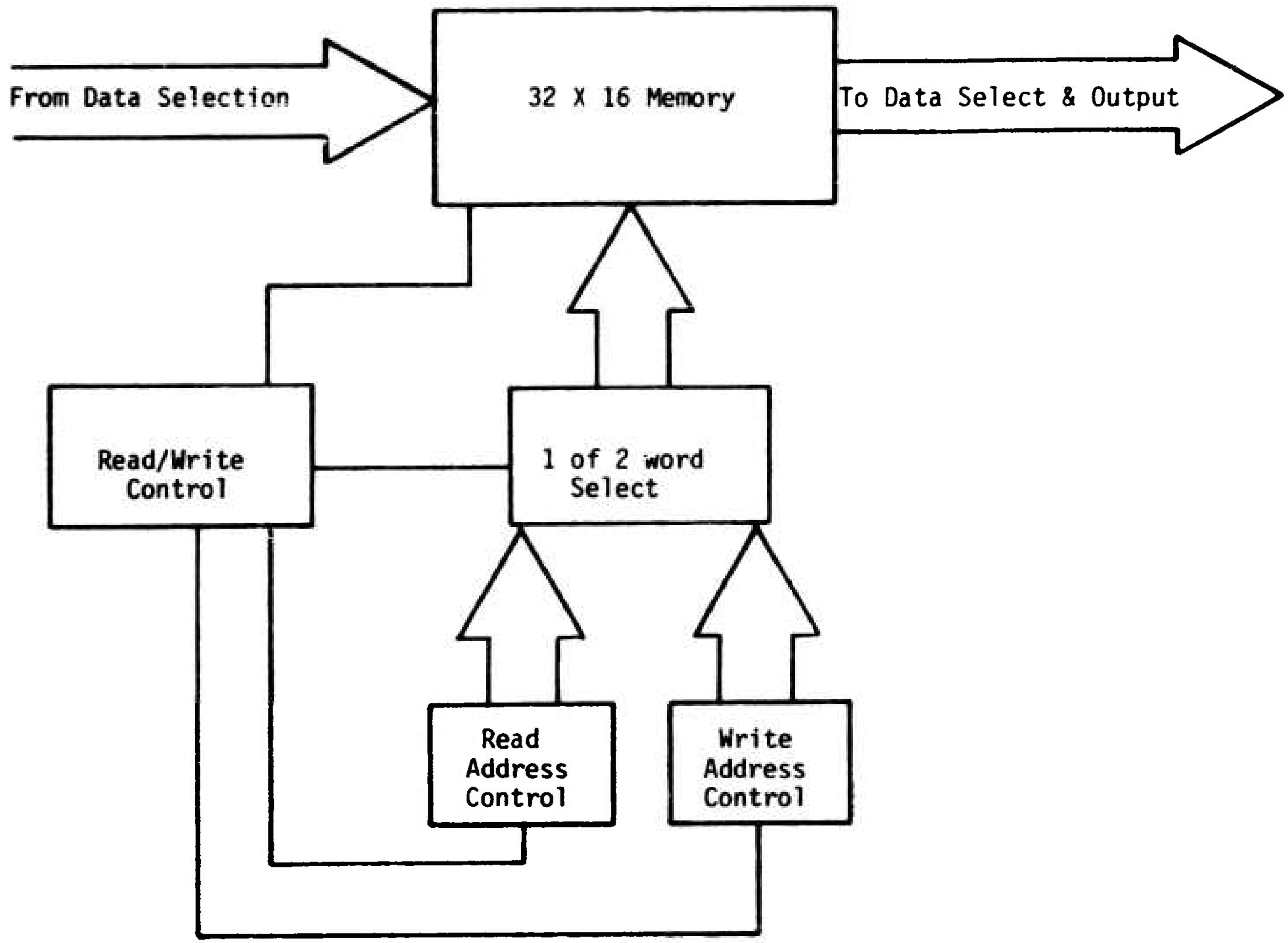


Figure 48: Memory

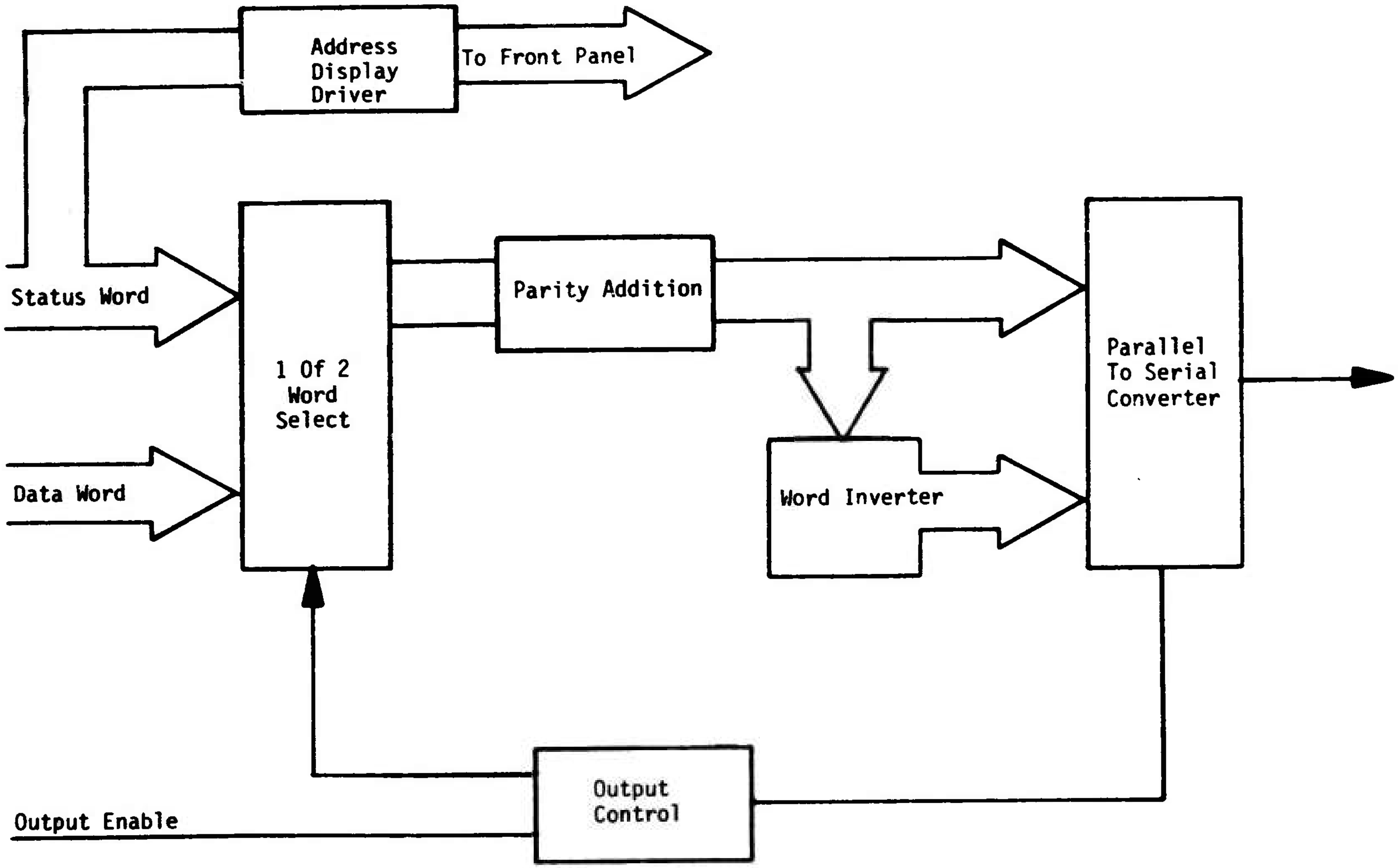


Figure 49: MTU Output

The read/write address lines are controlled by two 5 bit binary down counters. When a command word is received the word count is extracted from it and stored in the two counters. When these counters are counted down by the appropriate read or write commands they stop at zero, indicating to the timing and control sections that all of the data words have been received or transmitted. This dual function reduces the number of counters required in the MTU function.

iv. Output

The output section performs the function of converting the parallel data or status word into a serial Manchester word with sync and parity addition. This is accomplished by first adding a parity bit to the 16 bit parallel word. These 17 bits are then changed to a parallel 34 bit word by inverting this word and adding the inverted bits to it. To convert to a serial word, the parallel word is multiplexed by a 1 of 40 input multiplexer. The first 6 bits provide sync bit.

After the sync has been addressed, the first bit in the data word is addressed, followed by the inverse of this bit, followed by the second bit in the data word and then its inverse. This is continued until the parity bit has been addressed. If another data word is to follow the transmission of the previous status or data word, the first bit in the sync is addressed immediately following the inverse of the parity bit, there by allowing no delay between words. At this time a new data word is read from memory. The new data word is read and ready for multiplexing in the 300ns of the sync bit time. The multiplexer operates at a 20MHz clock rate so the output data will be the 10M bit data rate. Selection of either a status word or data word also selects either a positive or negative sync. When the last data word has been transmitted the output is held in the low state to prevent other transmission from occurring on the bus. Figure 49 shows the block diagram of the output section.

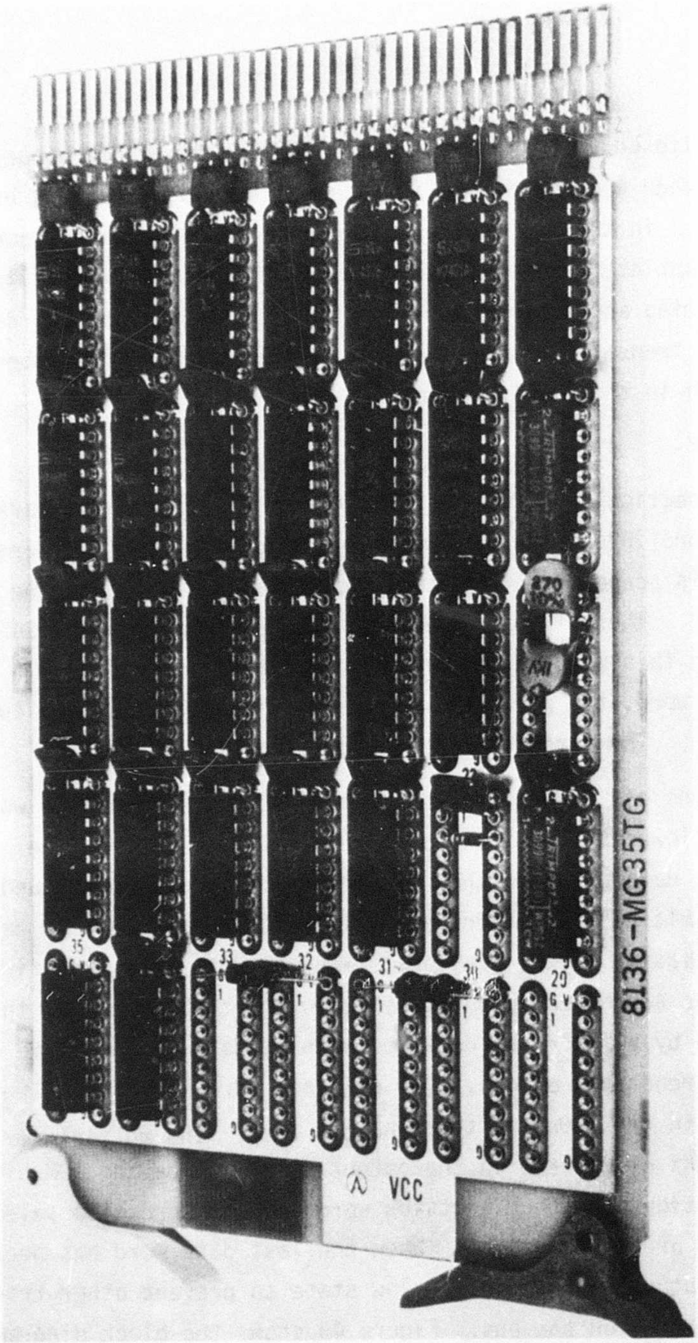


Figure 50: Timing and Control Board A1

v. Timing and Control

The Timing and Control section ties the rest of the sections together. It contains the logic functions such as gate, flip flops and counters to control data flow between the other sections, and provides the monitor functions to insure proper bus operation.

Construction of this section as well as the Data Selection, Memory and Output sections was made on a single plugable wire-wrap circuit board as is shown in figure 50. Construction on these wire-wrap boards provides for high density packaging without the expense of multilayer boards.

b. CMTU

Four of the MTU subsystems are used in the CMTU. These are

- o Receiver and signal condition
- o Sync Detection
- o Memory
- o Transmitter

i. Timing and Control

The main difference in the CMTU and the MTU is the timing and control sections. This section is controlled by command words received from the data bus in the MTU. In the CMTU however this section is controlled by the command lines of the CMTU controller interface.

ii. Data Select

The block diagram of the CMTU Data Select shows the similarities to the MTU Data Select (figures 47 and 51). The major differences are:

- o MTU checks address, CMTU checks for status errors.
- o MTU stores 11 bits of command word, CMTU stores 16 bits of status word.
- o Receipt of command word starts MTU bus function, receipt of status word usually ends CMTU bus function.

Transfer of status word and data words in CMTU Data Select is the same as transfer of command and data words in the MTU Data Select.

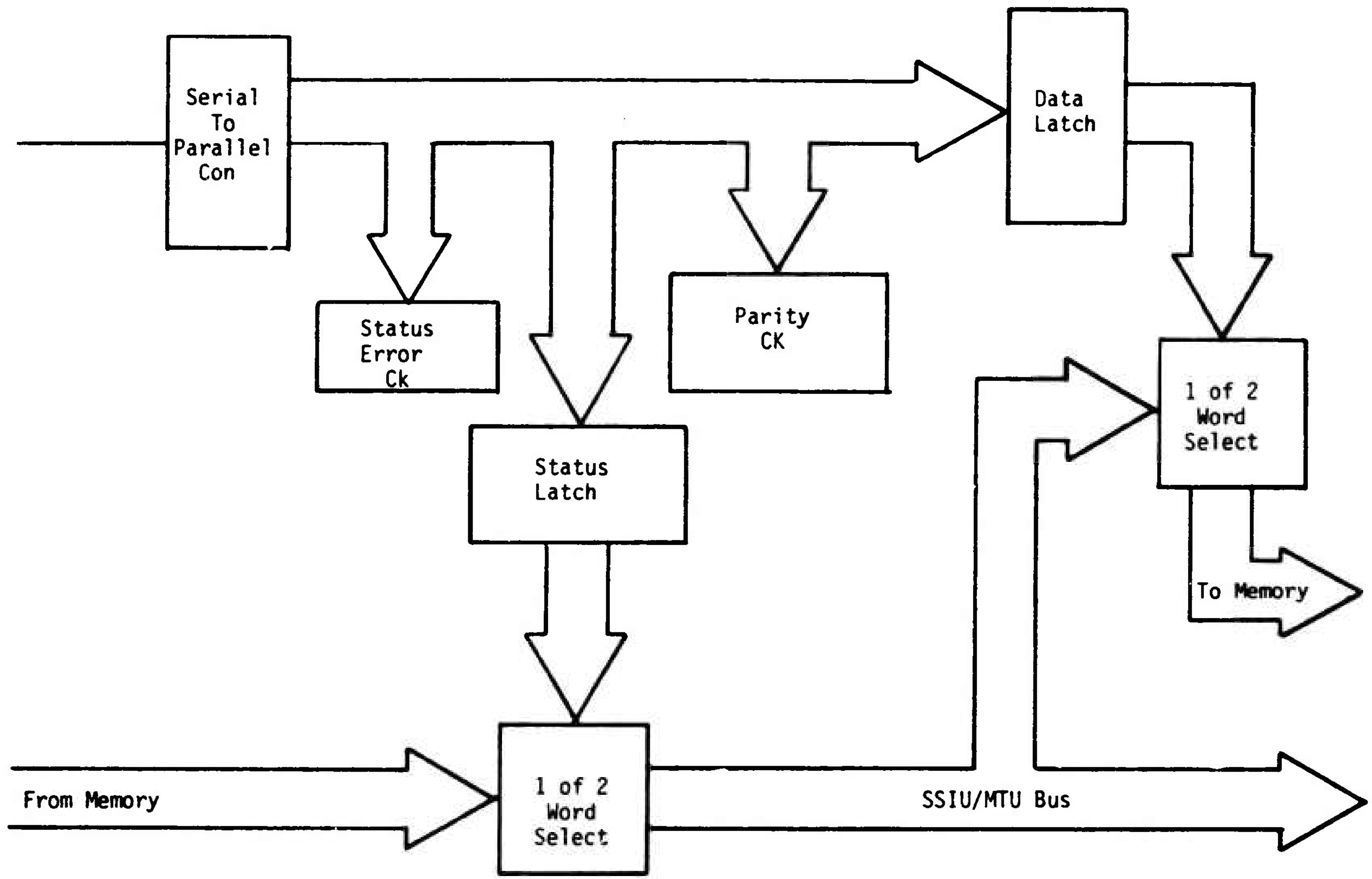


Figure 51: CMTU Data Selection

iii. Output

The similarities in the CMTU Output and MTU output are seen in the block diagrams of figure 49 and 52. The major difference in the two are the display driver of the MTU, the rest of the functions are the same.

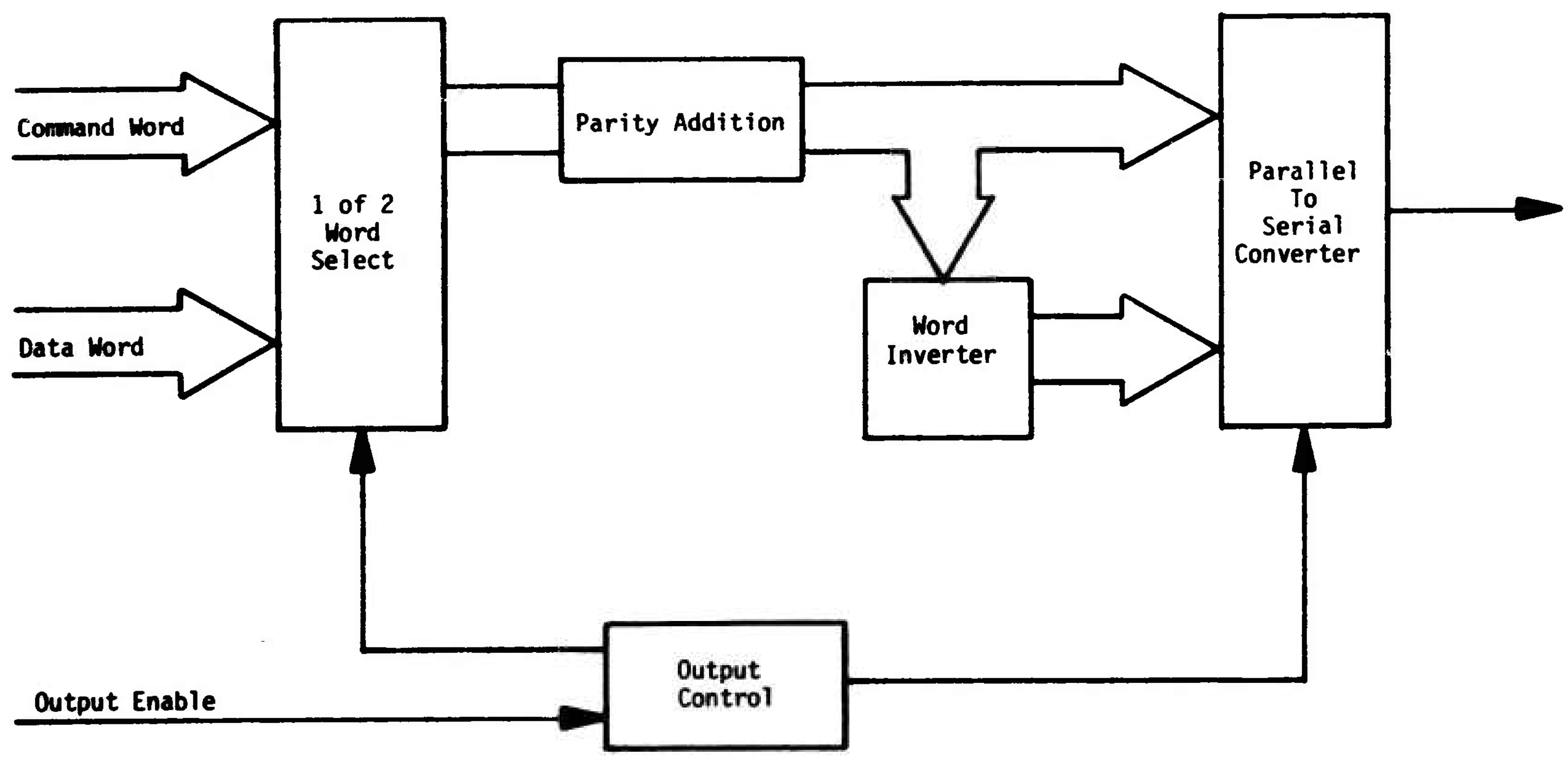


Figure 52: CMTU Output

SECTION IV

SYSTEM TEST AND OPERATION

1. Test Equipment

A stand alone test system has been constructed to demonstrate the capabilities of the EMI/EMP Data Bus. This system consists of two MTU Test Sets and one CMTU Test Set. The two MTU Test Sets will be used to check any two of the MTUs and the CMTU Test Set will be used to control the CMTU. The test configuration is shown in figure 53.

The MTU Test Set simulates the function of the SSIU. The MTU Test Set will either store data received from the MTU or transmit stored data to the MTU. The front panel of the MTU Test Set is shown in figure 54. The SSIU STATUS Switch controls the SSIU status bit in the MTU for error checks. The MTU POWER Switch provides for remote control of the MTU's power. The rear panel of the MTU Test Set is shown in figure 55. The SSIU interface connector provides the TTL level signals for interfacing to the MTU.

The CMTU Test Set simulates the function of the controller and provides some test on data words. The CMTU Test Set interfaces with the CMTU to control the data bus operation and simulate actual control signals, so the EMI/EMP Data Bus System can be exercised and tested using standard test equipment. The CMTU Test Set front panel, shown in figure 56, may be divided into 3 functional sections. The lower right section which controls the bus operations, the lower left section which controls the bus status and data words and the upper section which displays the status of the bus operations.

The Bus Operation Section is made up of four switches. These are:

- Transfer Mode
- Rate
- Reset
- Stop

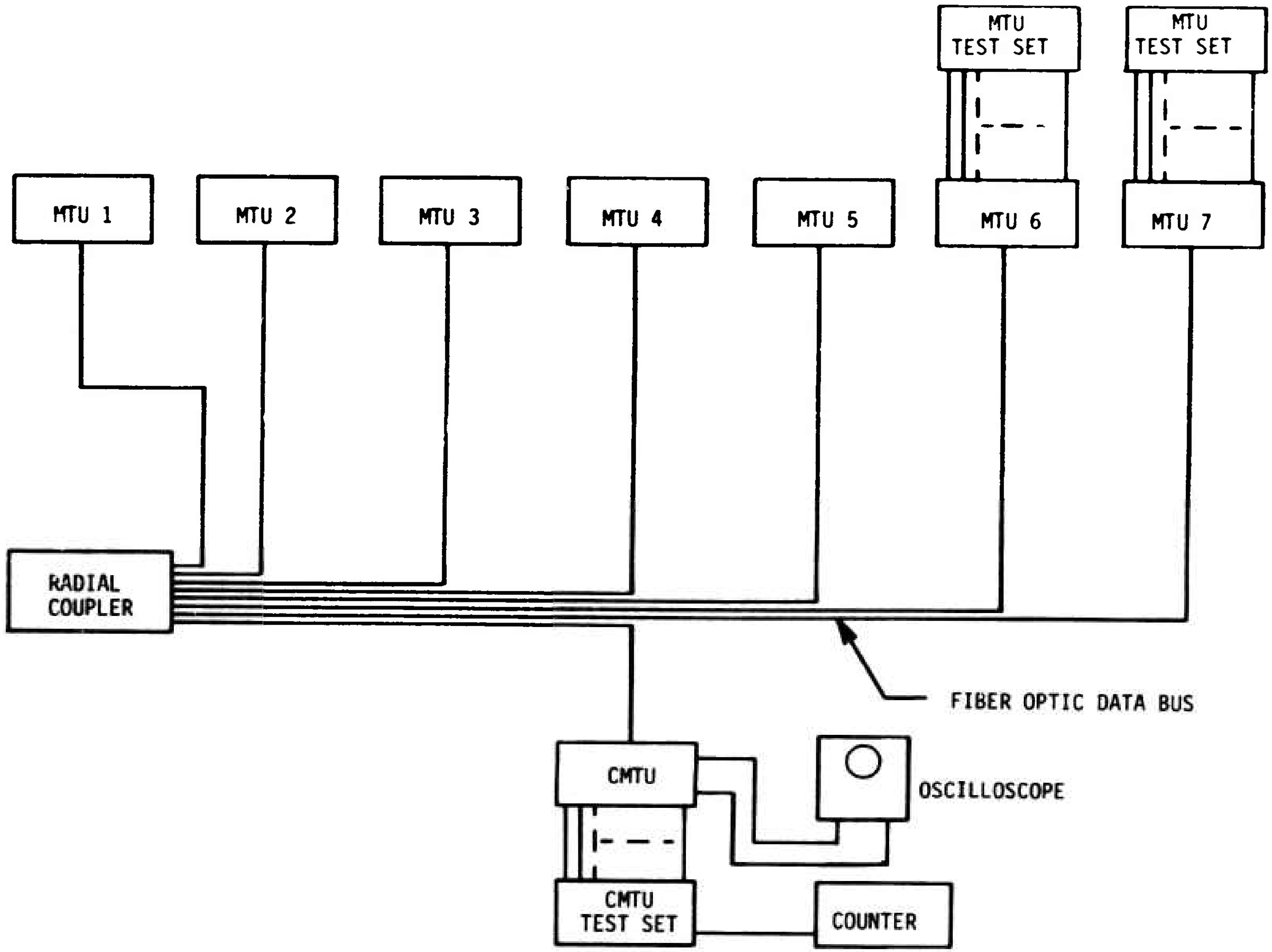


Figure 53: EMI/EMP - Data Bus Test Set Up

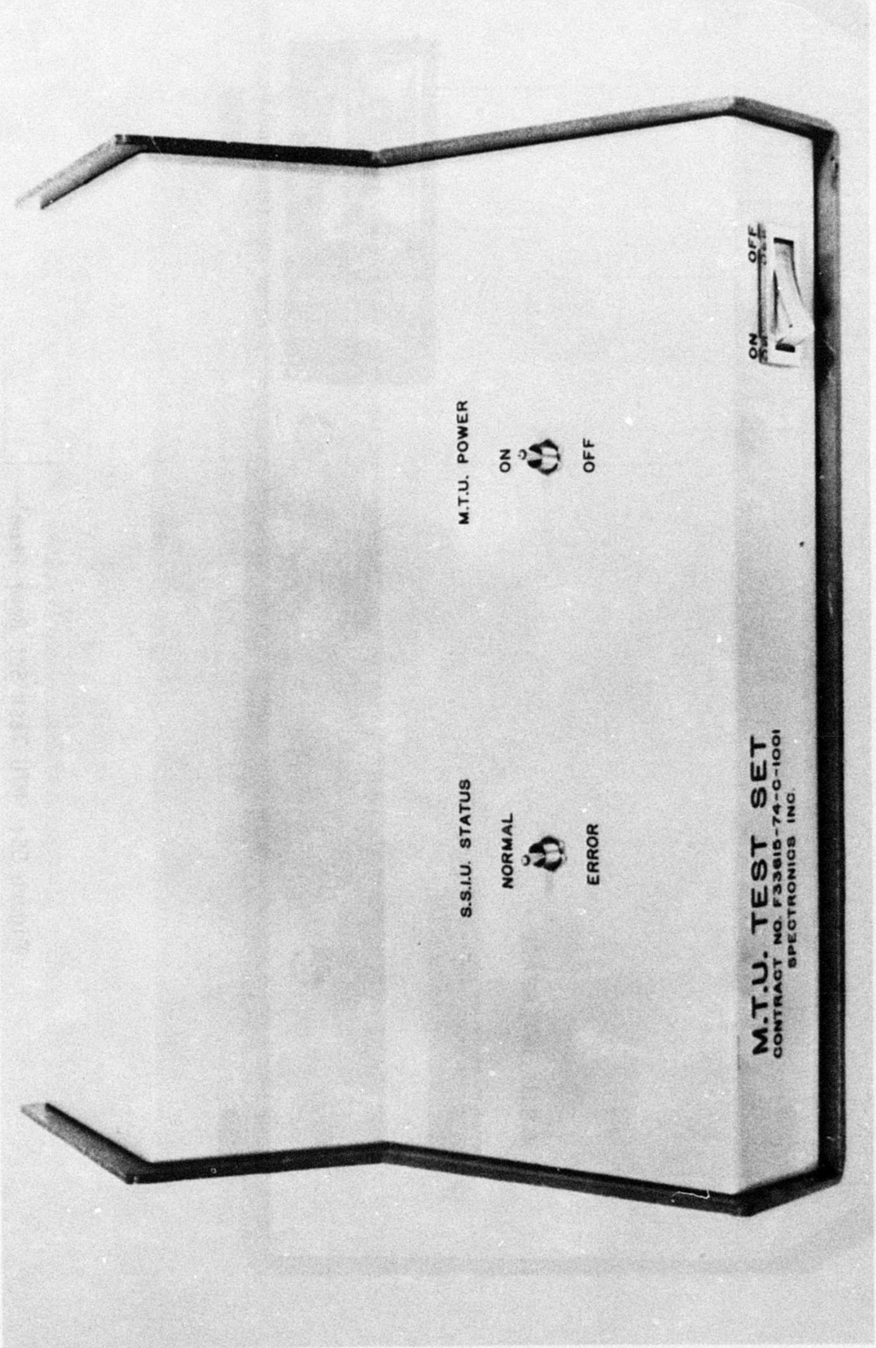


Figure 54: MTU Test Set

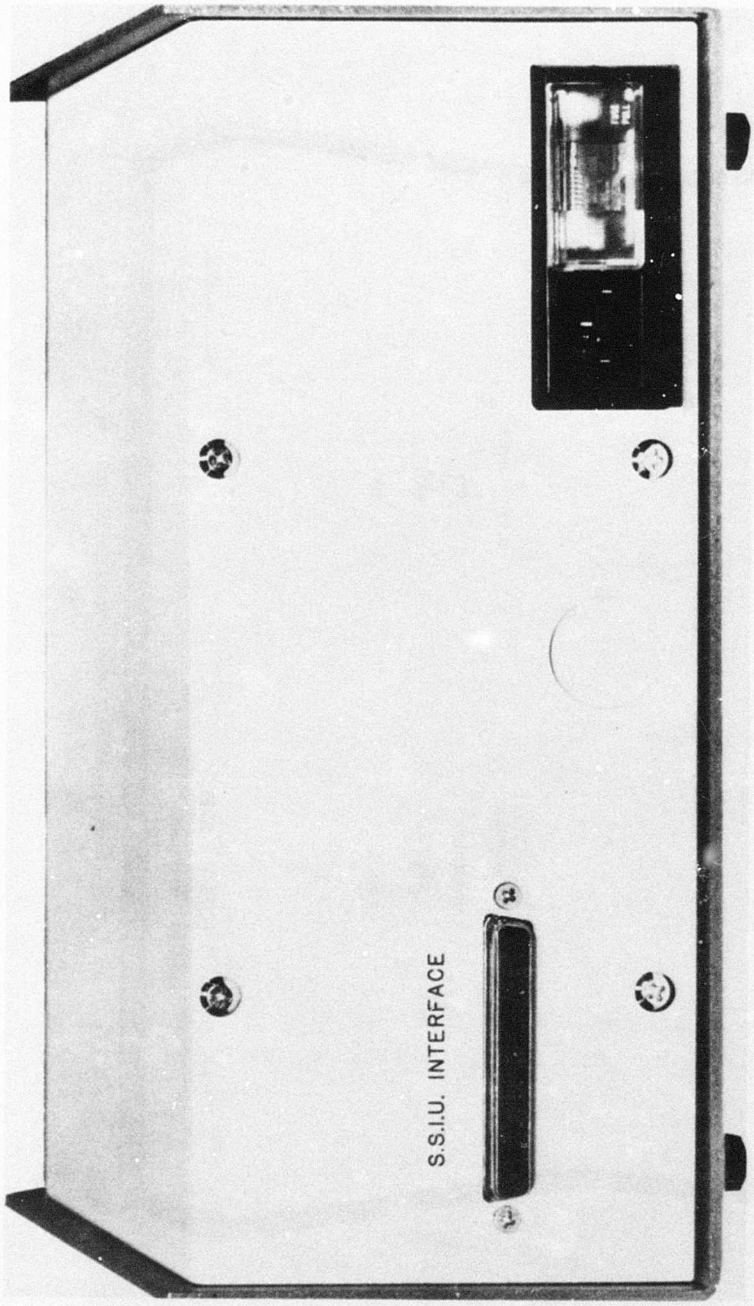


Figure 55: MTU Test Set Rear Panel

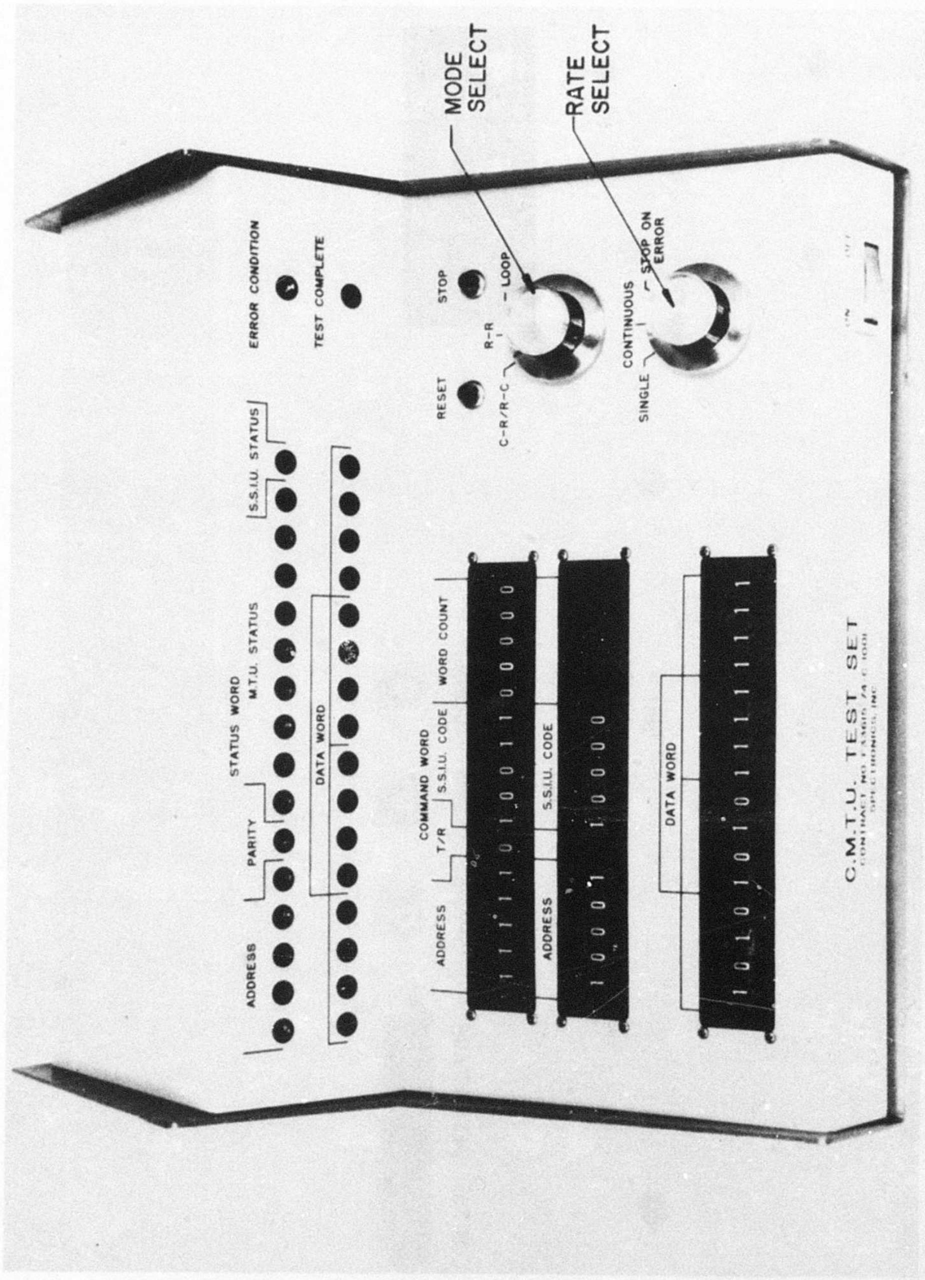


Figure 56: CMTU Test Set

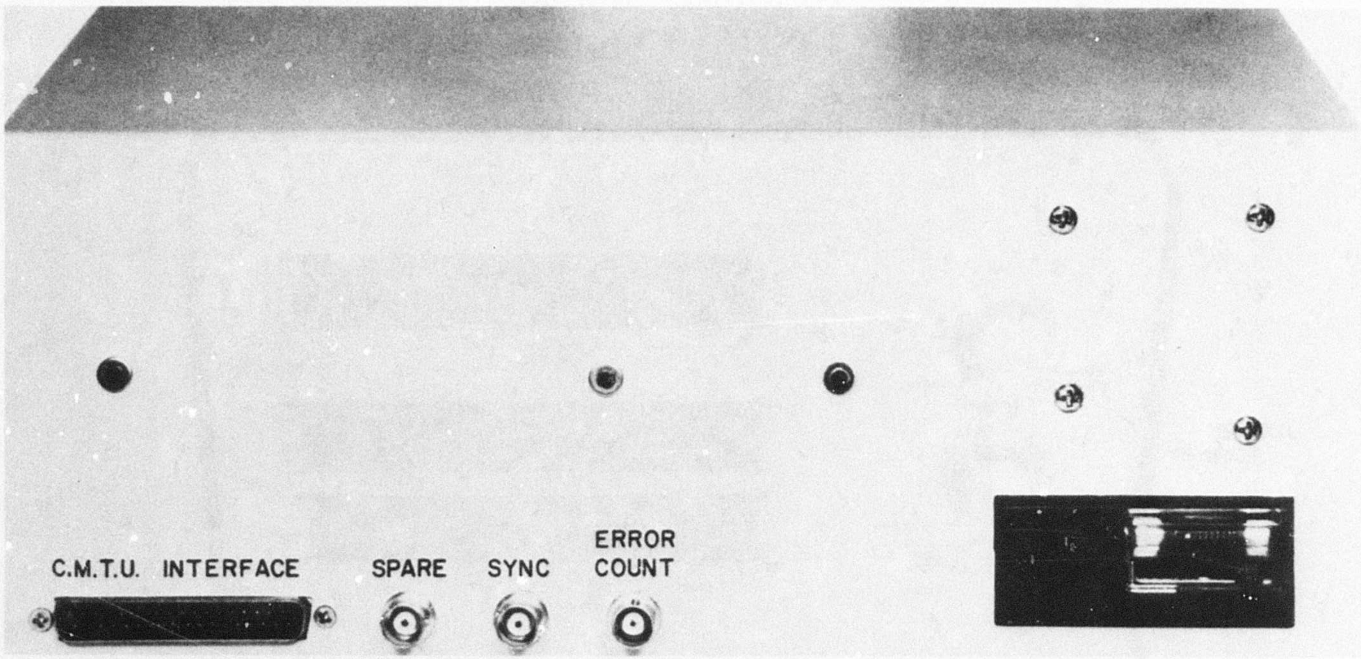


Figure 57: CMTU Test Set Rear Panel

The Transfer Mode Switch controls the bus operation by controlling the type of command (or commands) used on the bus. This is a three position switch. In the C-R/R-C position data is transferred between the Control MTU to a Remote MTU or is transferred between a Remote MTU to the Control MTU. In the R-R position, data is transferred from Remote MTU to another Remote MTU. In the Loop position data is transferred by all three methods.

The rate switch controls the number of times a bus operation takes place. In the SINGLE position, the bus operation happens only once. In the CONTINUOUS position, the bus operation is continuously repeated. In the STOP on ERROR position, the bus operation is continuously repeated until an error is detected. This error is then displayed.

The RESET switch is used to start the bus operation. In the single mode the RESET switch starts one bus operation each time it is pressed.

The STOP switch stops the bus operations.

The word control section is made up of three rows of thumbwheel switches. The top row controls the command word in CMTU to MTU transactions and controls the transmit command word in MTU to MTU transactions.

The second row of thumbwheel switches controls the command word to the receive MTU, in MTU to MTU transactions.

The third row of thumbwheel switches controls the data words that are to be transmitted by the CMTU. A comparison check is also made against the received data word and this data word to check for errors.

The display section displays the received status word from the MTU. It also displays the received or transmitted data words of the CMTU. The ERROR CONDITION display indicates an error has occurred. The TEST COMPLETE display indicates the bus operation is stopped.

The rear panel of the CMTU Test Set, shown in figure 57 provides the following output connectors:

CMTU Interface

Sync

Error Count

Spare

The CMTU INTERFACE connector provides the TTL level interface to the CMTU. The SYNC output provides a negative sync signal to be used by an oscilloscope. The ERROR COUNT output provides an output pulse for each error detected. This is used by a counter to totalize the error over a given period of time.

2. System Evaluation

The system evaluation is broken down into evaluation of the three design phases. The evaluation of the optical bus and the optoelectronic interface is done on a separate basis.

Finally the entire system is evaluated on a stand alone basis using the supplied test equipment.

a. Optical Bus

Measurements taken on the completed optical bus shown the maximum attenuation between different arms of the bus to be 42dB. The minimum attenuation was 34dB with the average being 38dB. These measurements were taken using two different methods.

The first used a single light emitting diode to inject a signal into each of 7 arms of the optic bus while the signal was monitored at the remaining arm. The second method used the signal output of each postamp while each of the remaining stations are transmitting.

Both methods are in good agreement, so the second method is considered here, as it represents a true picture of actual bus operation. To calculate the attenuation the following considerations were used.

10.5dB	LED to FO Bundle Coupling
9.5dB	Splitting of Power in Radial Coupler
4.4dB	Loss in Radial Coupler
6.4dB	FO Bundle to Coupler (calculated)
.5 to 4dB	Loss in 20 to 100 ft. of FO Cable
.5	Front surface reflection
31.8 to 35,3dB	Total

The measured losses in the data bus have an excess of 2 to 6dB. This excess was again determined to come from the termination of the Valtec fiber bundles. This excess loss is in the fiber bundle/radial coupler interface and is on the order of 3dB.

The total dynamic range on the bus from the measured values of attenuation is 8dB. The dynamic range is calculated from the following considerations:

1.4dB	Dynamic range of Coupler (maximum)
3.5dB	Dynamic range due to Fiber Bundle lengths
.8dB	variation in LED output
5.7dB	Total

This leaves an excess of 2.3 dB which is easily accounted for in the variation in coupling to the fiber bundles from the light emitting diode and coupler.

b. Optoelectronic Interface

Measurements were made in the postamp and signal conditioning section to determine its maximum operating potential. Signal levels were measured at the input to the voltage comparator to calculate the actual performance of the system. These measurements are as follows:

Maximum Signal Level	2.5V P-P
Minimum Signal Level	.400V P-P
Noise Voltage	.017V rms

The reference level at the input to the comparator comes from the peak detector and is half (1/2) the signal level. However, to prevent error from occurring in the no signal condition, the reference level is never allowed to drop below .100 volts. So, the minimum input signal that can be properly decoded is .200 volts.

The S/N ratio is the ratio of the magnitude of the difference in the signal level and reference level to the rms noise voltage. The reference level is 1/2 the peak to peak signal level so the magnitude of the difference in the peak to peak signal and reference level will be 1/2 the peak to peak signal at the optimum sample time.

$$S/N = \frac{|e_s - E_{ref}|}{e_n} \qquad (18)$$

For the minimum signal level:

$$S/N = \frac{|.4 - .2|}{.017} = 11.8 \qquad (19)$$

For the no signal condition

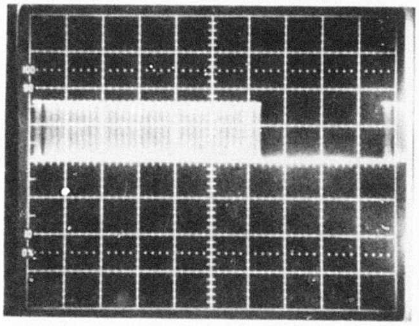
$$S/N = \frac{|0 - .1|}{.017} = 5.9 \qquad (20)$$

The no signal condition also represents the worst case signal to noise condition at the comparator input. The signal to noise in the off condition is 5.9 to 1. This is close to the 5.62 to 1, reference 6 (p 122), required to give a bit error rate of 1 x 10^{-8}, however, the sync and data formats required in the digital electronics makes the probability of an error condition occurring in the off condition nearly non-extent. Therefore, the worst case signal to noise of 11.8 to 1, is realized when the minimum signal is received.

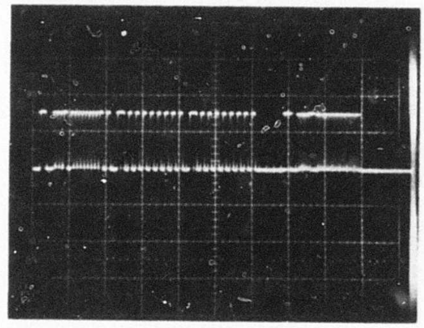
The above signal to noise levels represent the maximum realizable levels in the data bus system. The actual signal to noise in the system will be less because the data will not always be strobed when the signal is at its peak. This is due to clock errors that occur in the clock recovery schemes necessary in an asynchronous data bus, plus the fact that the signal will not always be at the peak level at the T/2 strobe point due to bandwidth limitations in the preamp and postamp. However, accurate bit error rate measurements can be made using digital techniques on the system level. These measurements along with future study are necessary to determine the actual signal to noise requirement in a data bus system.

The data bus system uses a 10M bit/s optical Manchester data rate on the bus in a 10 to 1 scale-up of the requirements of reference 1. However, the unipolar optic Manchester signal does not allow the data bus operation to realize all of the advantages of the Manchester signal used in an equivalent electrical system or in a point to point optical system. The electrical signal is bipolar and has zero average value so that the signal level or data sequence has no effect on the reference level. The point to point optical signal is relatively constant, so with AC coupling the effective signal is bipolar and offers the same advantages as the electrical signal.

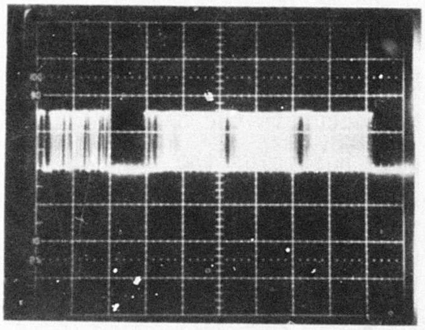
The unipolar optical signal on the data bus requires an effective DC coupled signal with peak detection to be properly decoded. If the sync



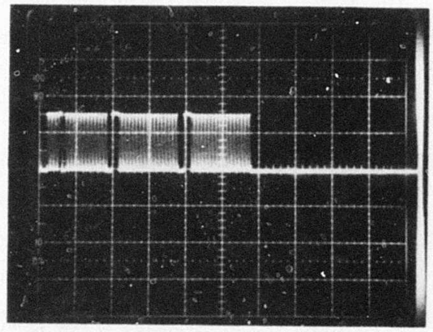
(1)
Transmit 32 Words



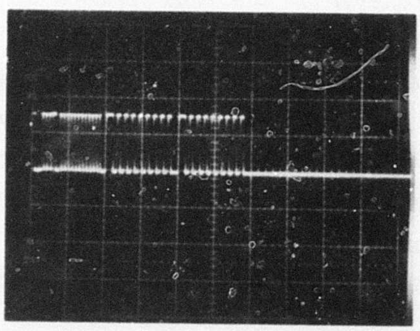
(2)
Receive 2 Words



(3)
Transmit 2 Words



(4)
Transmit 2 Words
1111111111111111



(5)
Transmit 2 Words
1010101010101010

Figure 58: Data Bus Transmission I

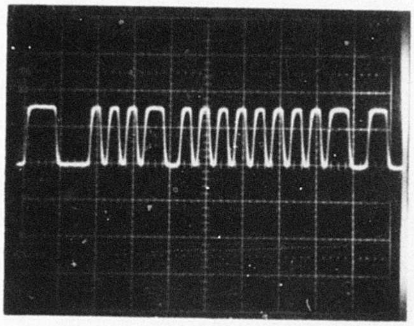
signal is used for the clock information as is in this data bus system, the Manchester signal is not needed. With the use of an NRZ format the system bandwidth can be reduced to half (1/2) the requirement of the Manchester format. Since the input noise is proportional to bandwidth the signal to noise can be improved a factor of two (3dB) with the same data rate.

c. System Operation

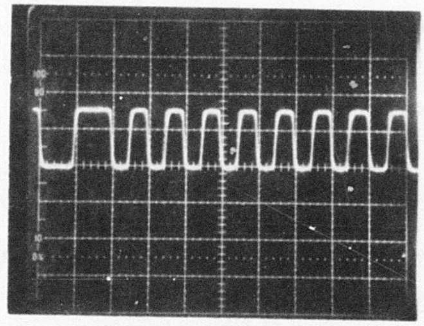
Operation of the system on a stand-alone basis demonstrates the true capabilities of EMI/EMP resistant data bus. Operation of the bus is on a simplified basis so that the entire operation can be monitored with an oscilloscope and a totalizing counter.

Operation of the bus in the continuous mode will allow the bus to be monitored through the data output connector of the CMTU. In this mode of operation the same bus command is continuously repeated so that it can be displayed on an oscilloscope. Figures 58 and 59 show the oscilloscope display for the various operations. In figure 58, Display 1 shows an entire transmit command of 32 words. The first portion is the command word followed by a small delay and then the status word followed by 32 data words. The delay at the end of the last data word is the time required to transfer the 32 data words to the controller. Display 2 shows a receiver command where the first word is a command word followed by two data words, then a delay followed by the status words. Display 3 shows a transmit command of two words. Notice that the status words in Displays 2 and 3, and the data words in 3 are not in sync with the command words. This is caused by the asynchronous operation of the data bus. Displays 4 and 5 are synchronized to the status word so the command words are not visible.

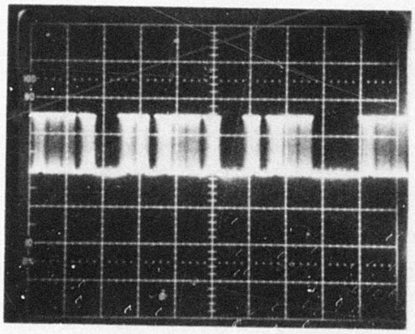
In figure 59, Displays 1 and 2 are expanded to show a full command and data word. Display 3 shows a complete loop cycle. The first word is a receiver command followed by two data words, a delay and then a status



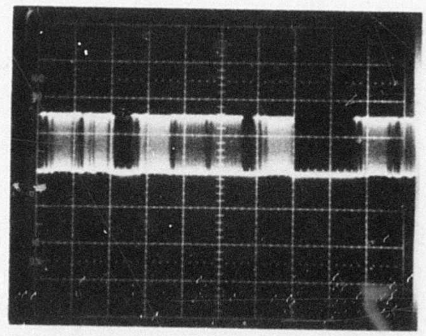
(1)
Command Word
0000100000000010



(2)
Data Word
1010101010101010



(3)
Loop Mode



(4)
Remote to Remote

Figure 59: Data Bus Transmissions II

word. The next two words are a receiver and transmit command followed by a delay, a status word, two data words, a delay and then another status word. The final command word is a transmit command followed by a delay, a status word and two data words. Display 4 shows a remote to remote command where the first two words are a receive and transmit command followed by a delay, a status word, two data words, a delay and the final status word.

Errors that occur in the bus operation can be displayed in the status and data displays by operating the bus in the stop on error mode. In this mode the bus will operate in the continuous mode until an error condition is detected. At this time bus operation is stopped and the error displayed in either the status word display or the data word display.

To totalize errors, the bus is operated in the continuous mode and a counter is connected to the error count output of the CMTU Test Set. Errors are counted over a period of time to give a good average of the bit error rate. A bit error rate of 1×10^{-8} will give an average of four (4) errors per minute.

An accurate measurement of the bit error rate of the data bus system has not yet been determined due to the time available and the number of combinations of bus operation. To give an example, there are 56 ways for transmission to occur between two of the eight terminals provided the way the bus is connected is not included. If the possible number of bus connection combinations are included, there are 2,257,920 possible combinations of different operations that can occur on the bus. However, the connection of the data bus is not expected to have much effect on the operation of the data bus as the dynamic range of the bus is low. The measurements made on the bus so far show the bit error rate to range from 5×10^{-9} to 1×10^{-11}.

SECTION V
CONCLUSIONS AND RECOMMENDATIONS

An EMI/EMP resistant data bus has been designed, fabricated, and demonstrated which meets or exceeds all of the speifications set forth in the contract document. This optoelectronic data transfer system has been implemented using non-coherent light emitting diodes, flexible multi-mode fiber optic bundles and silicon p-i-n photodiodes. The system uses a nine (9) port radial coupler to implement a true optical bus. The bus has 8 stations with a maximum length of 100 ft. The system features a pluggable optical interface at the station and at the radial coupler. Optical signals are coded in a unipolar Manchester format with a 10M bit/s data rate and a bit error rate of less than 1×10^{-8}.

The effort on this program covered three separate areas required for the development of an optical data bus system. The areas are:

- The development of a low loss passive radial coupler.
- The further development of the optoelectronic interface requirements.
- The development of a Multiplex Terminal Unit to implement the multiplexing required by the bus.

In the passive coupler effort investigation was made on both the in-line and radial coupler bus systems as was reported earlier. The realization of the performance advantage offered by a radial coupler over T couplers is further influenced by the development of a radial coupler using a rectangular scrambler road and solid side arm. This radial coupler offers:

- Low dynamic range in the data bus system.
- A total coupler insertion loss of only 4.4dB.

- The fact that only one additional fiber bundle interface loss is added, in the system, at the exit port of the radial coupler.
- Minimal addition losses with the addition of new stations (3dB total in going from 8 stations to 16 stations).

Further development is still needed in the final development of the radial coupler as it is estimated that the insertion losses in the radial coupler design can be further reduced to order of 1dB.

The efforts in the development of the optoelectronc interface has led to the development of methods to handle the optical unipolar signal in a data bus environment. Further study is needed in this area, however, to determine optimum data coding techniques for the unipolar signal. The Manchester code used in the data bus gives the required performance needed for a bit error rate of 1×10^{-8}, however, is not the optimum technique for maximum signal to noise. The benefits of the Manchester code are not realized in a data bus system that must rapidly track unipolar signals over a dynamic range of even 3dB; therefore, the wider bandwidth requirements of the Manchester code results in an unnecessary loss in signal to noise. If a NRZ data format were used on the optical bus, the system would require half the bandwidth of the Manchester code and result in a 3dB signal to noise improvement. Also, further development is needed in the recovery of clock as the technique used in the data bus is not practical at the higher data rates, where a 100M bit/s data rate would require a 1GHz clock.

The effort in the development of the data terminal was for the implementation of the optical bus to interface with standard digital interfaces of the 1M bit/s shielded twisted pair system. The implementation of this terminal was accomplished using standard SSI and MSI logic components. Presently there are no LSI logic elements capable of handling the requirements of 10M bit/s or higher data rates. Further developments will be needed in the area of high speed LSI logic elements to realize high speed data terminals with the same physical sizes obtainable in the lower data rate systems.

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