MEASUREMENT OF THE LOSS IN OPTICAL FIBRES

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By

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ABSTRACT

The equipment necessary to measure the loss in an optical fibre has been constructed. The details of the design and the results of testing the equipment are given. This equipment was designed to measure the loss induced in fibres by ionizing radiation, but can also be used to measure undamaged samples. A "dual-beam" system is used to increase the accuracy of the equipment.

The equipment will measure the spectral attenuation of an optical fibre to an accuracy of ±1 dB/km between .9 and 1.65 μm if the fibre is at least 175 m long and has an attenuation of less than 115 dB/km. Simple modifications to the equipment would reduce the sample length required for ±1 dB/km accuracy to 60 m.

The minimum sample length is determined by the accuracy with which samples can be connected into the system. The maximum sample attenuation is determined by the signal to noise ratio. Methods of increasing the signal to noise ratio and the sample connection accuracy are discussed. Calculations based on the suggested improvements show that the sample length can be reduced to 45 m and the maximum attenuation increased to 750 dB/km for ±1 dB/km accuracy. The use of a testing method which does not require removal of the sample could give ±1 dB/km accuracy for 10 m samples.

The operating and adjustment procedures for the equipment are given in the appendices to this report.

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CHAPTER 1

INTRODUCTION

The transmission loss of optical fibre is important because it is one of the prime factors which determine the maximum transmission distance through a fibre-optic link. Many studies of attenuation have been done and regions of low loss have been identified. For silica based fibres these regions are .8 to .9 μm and 1.1 to 1.4 μm. The lowest loss is usually found to be near 1.3 μm for silica fibres. Since silica fibres also have minimum dispersion near 1.3 μm, this region is of very great interest for long range, high speed communications. Most of the studies of attenuation have been carried out on "new" fibre, however, the system designer must also know how the attenuation of a fibre will change during the design lifetime of the system due to aging and environmental effects. Optical fibres have been in use a relatively short time compared to the expected lifetime of a modern communications link and there is no trial data on the attenuation change for, say, 10 years of installation.

One factor which has been shown to increase the attenuation of glass optical fibres is radiation such as gamma rays and neutrons (see for example ref. 1). Radiation is normally present in low doses in the environment due to cosmic rays and the radioactive elements found in the earth. This background radiation has been reported to amount to 10 Rads over 20 years [2]. In military, space or nuclear energy applications, fibres may be subject to radiation in high doses on a continual or intermittent basis.

The studies of radiation damage which have been done indicate that 10 Rads administered over a short period of time causes a large increase in attenuation in some fibres and a small increase in other fibres (measured at approximately .8 μm). The studies also showed that the attenuation due to exposure to radiation may anneal out over a period ranging from hours to days. One cannot, therefore, definately say that over 20 years a susceptible fibre will show additional loss due to background radiation. Understanding of both the damage mechanism(s) and the annealing process(es) will be necessary to predict the long term effects from short term studies.

The studies of radiation-induced attenuation also showed that the attenuation is frequently most severe for short wavelengths. In the visible region (.4 to .6 μm) the attenuation was as high as 40 dB/km for every Rad of radiation[1]. The induced attenuation for other fibres was very low (less than 0.1 dB/km per Rad) for wavelengths between 1.0 and 1.4 μm[1]. Still other fibres had an attenuation minimum near 1.1 μm after which the attenuation increased again[1]. Since the low initial attenuation of fibres for 1.3 μm light will probably lead to very long transmission links the study of radiation induced attenuation in this region is particularly important.

The purpose of this project was to construct a fibre transmission measuring system to measure accurately the attenuation induced in glass optical fibres. The accuracy goal for the system was ±1 dB/km of attenuation. Attenuations ranging from ±1dB/km for undamaged samples to tens of thousands of dB/km for heavily damaged samples were expected. The wavelength range of interest is approximately .7 μm to 1.8 μm. The fibres to be tested are typically silica types with core diameters ranging from 50 μm to 100 μm but the system is not necessarily restricted to these types.

The optical power which can be launched into the fibre, the noise equivalent power of the system, the repeatability of the transmission measurement and the sample attenuation determine the sample length required to achieve an accuracy of ±1 dB/km in the measurement. Accuracy is not the only determining factor in choosing the sample length. The length is limited by the space available in the radiation sources, particularly the "rabbits" used to transport the fibre into the reactor(1).

The "equilibrium length" of a fibre is the length of fibre in which the lossier modes are damped out so that an equilibrium mode distribution, independent of the source characteristics, is established. The measured attenuation of optical fibre is a function of the sample length for samples which are shorter than the equilibrium length(3) but is constant for samples longer than the attenuation length. The equilibrium length ranges from tens of metres to kilometres for undamaged fibres. Sample lengths are expected to be less than 100 m and may therefore be less than an equilibrium length thus to make a useful comparison all samples, particularly of a given type, should be the same length (assuming that the equilibrium length does not change due to the radiation).

The attenuation in dB/km is extrapolated from the transmission of a length of fibre using the equation below.

$$A = (10 \log T) \cdot (1000)/x \qquad (1\text{-}1)$$

where: A - attenuation in dB/km

T - sample transmittance

x - sample length in metres

It is important to state the sample length when the induced loss is given as an attenuation in dB/km if the samples are less than an attenuation length (as discussed above).

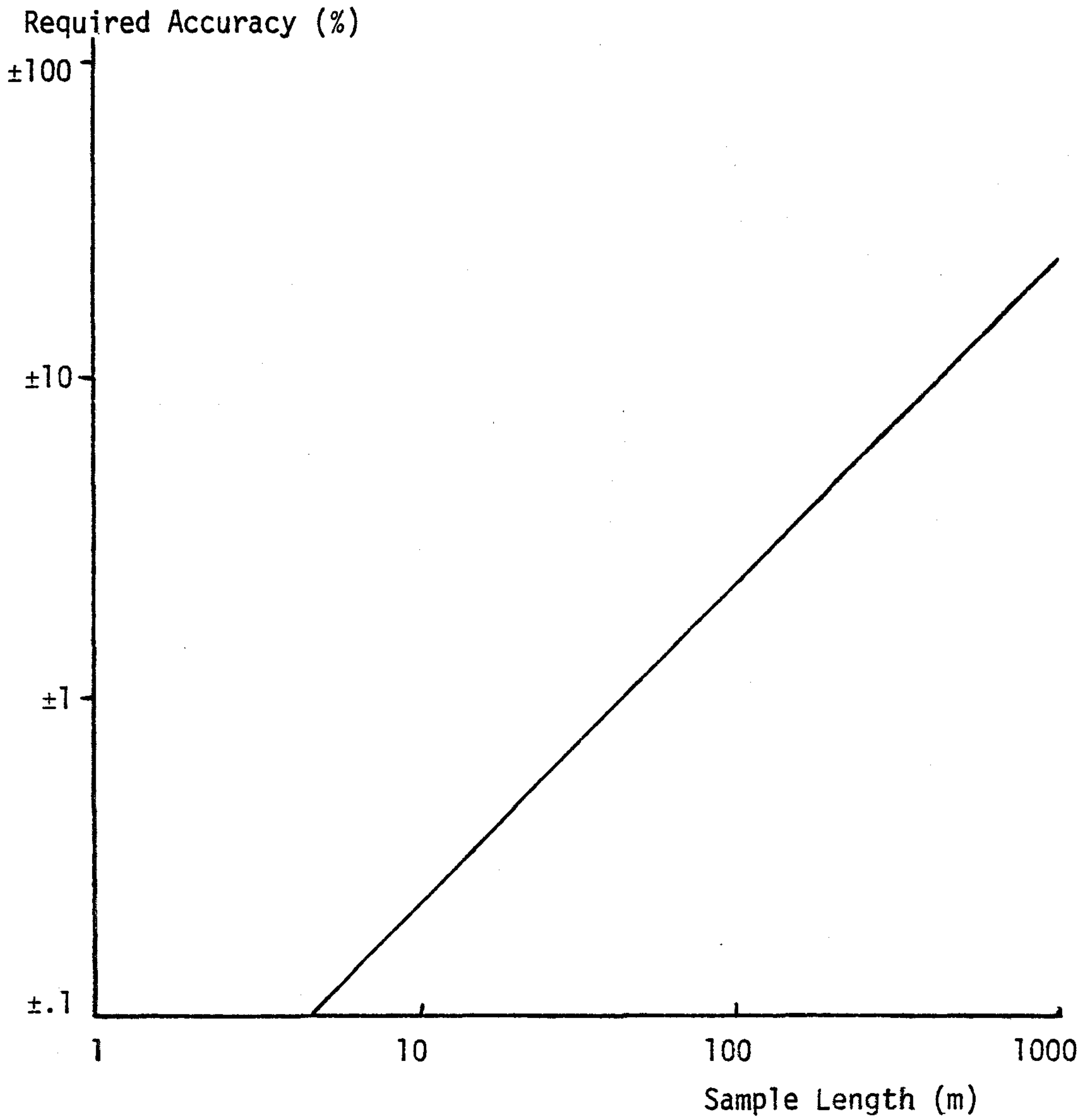
The percent error in the transmission measurement which results in a 1 dB/km error in attenuation, E, is given by:

$$E = 100(1 - 10^{-x.10^{-4}}) \qquad (1\text{-}2)$$

where x is the sample length and E is the percent transmission error. This is plotted in figure 1-1 for samples from 1 m to 1000 m. The error in the transmission measurement includes all sources of error in the system but not noise.

Noise determines the minimum sample transmission since, to compensate for low sample transmission, the signals must be amplified. This amplification eventually increases the noise amplitude until the output cannot be determined with sufficient accuracy unless the scan rate is made impractically slow. The transmission of a sample depends exponentially on its length, thus the minimum transmission corresponds to a maximum sample length (for

Figure 1-1



Accuracy Required to Measure Induced
Loss to ±1 dB/km

a given attenuation).

The sample must be long enough to provide enough accuracy and short enough to provide enough signal and to suit the radiation source. The limitations imposed on the system by these conflicting requirements are analyzed in Chapter 3.

CHAPTER 2

THEORY OF OPERATION

This chapter gives a description of the entire fibre transmission measuring system. The functions and characteristics of all of the components of the system are discussed. Methods of coupling fibres into the system and of reducing the system noise are also discussed.

The system measures the transmission of a sample fibre relative to the transmission of a reference fibre. This system, which is similar to a dual beam system in a spectrophotometer, was adopted because it reduces the effects of fluctuations in lamp output, coupling of light into the fibres and detector responsivity changes.

Figure 2-1 is a block diagram of the system. The light source provides chopped filtered light to the monochromator. The output of the monochromator is a cone of light which has an adjustable spectral width. This light is focussed onto two pickup fibres in the output adaptor. These two pickup fibres, one to be coupled to the sample fibre and the other for the reference channel, can be employed in several testing configurations as discussed later. The light leaving the sample and reference fibres is detected by the sample and reference detectors located in the detector/preamp box. Also in the detector/preamp box are a pair of matched preamps which

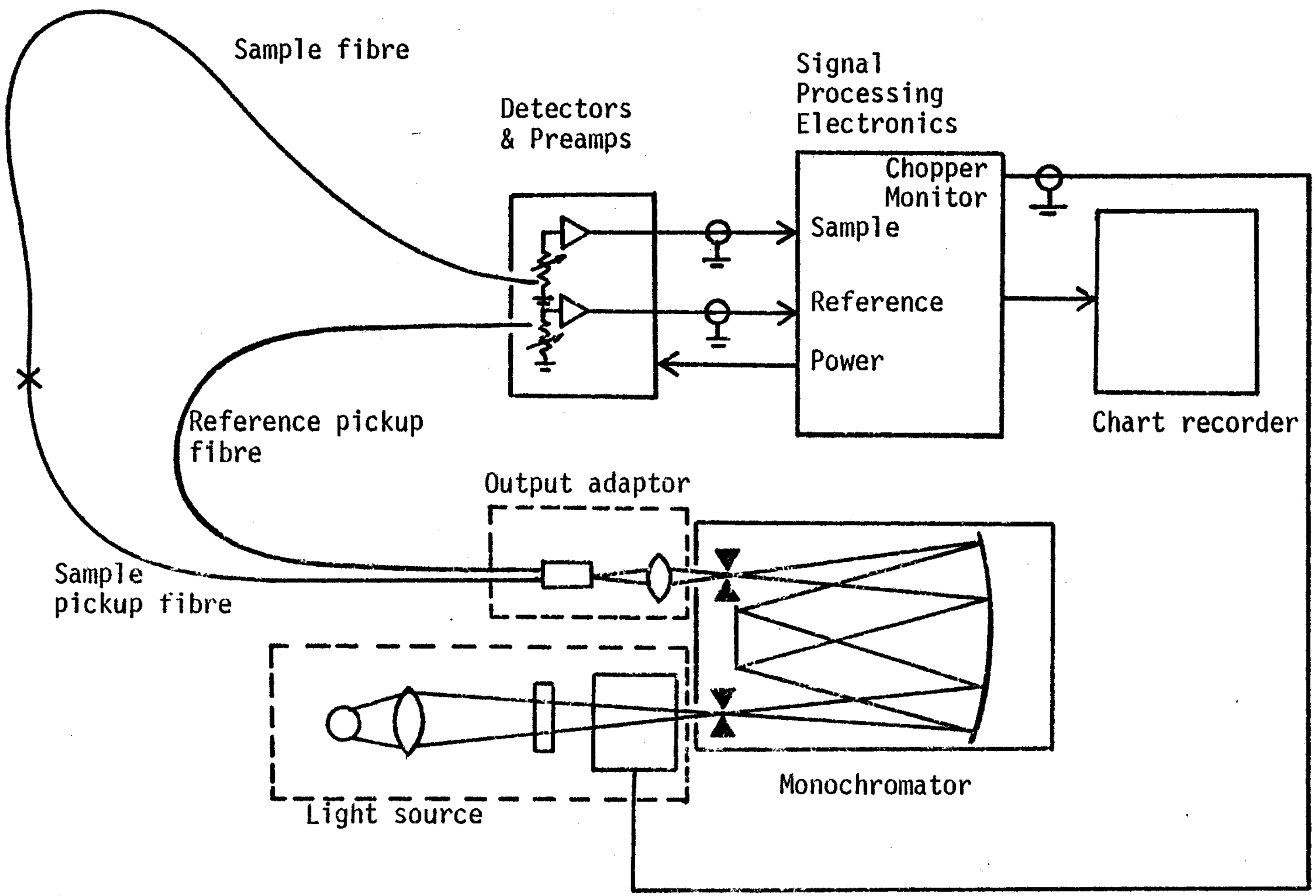


Figure 2-1

Block Diagram of the Transmission Measuring Equipment amplify the detector signals from millivolts to volts. The processing electronics converts the (pulsed) sample and reference signals to DC levels which go to a divider circuit (also part of the processing electronics). The divider output is the ratio of the sample level to the reference level. It is therefore proportional to the sample transmission. The output is plotted on a chart recorder. The sample transmittance or more commonly the change in sample transmittance (due to radiation damage) is obtained by multiplying the divider output by the appropriate proportionality "constant" which is usually a function of the wavelength. The proportionality constant depends on which fibre testing method has been used.

The fibres to be tested will normally be in sets. Each set consists of a number of fibres of one type and of the same length at least one of which is undamaged (the "standard" fibre). The rest of the fibres in the set have varying damage levels. The damage is measured by comparison with a standard fibre. There are three methods for testing these sets of fibres.

The first method, called the "long-short" method is useful if the absolute transmission of a fibre is of interest. Initially the fibres are configured as follows. The reference pickup fibres goes directly to the reference detector. The sample pickup fibre is connected to one end of the sample fibre. The other end of the sample fibre goes to the sample detector. The output for this configuration is recorded and then the sample fibre is cut about 0.5 m from the detector. The free end of the 0.5 m (short) sample is then connected to the sample pickup fibre, without disturbing the sample/detector joint and the output is again recorded. The ratio of the output obtained for the full sample to the output obtained for the short sample is the absolute transmission of the remaining sample. Because the sample becomes considerably shorter every time it is tested, this is not a good method of testing short samples which are to be studied periodically. The long-short method is best used to characterize samples in undamaged condition. The induced loss of a damaged fibre can better be obtained by the methods described below.

The second methd compares each (damaged) sample fibre directly to the standard (undamaged) fibre. This is done by connecting the standard fibre into the reference channel (between the reference pickup fibre and reference detector) and connecting each sample in turn into the sample channel. Assuming that the 100% level of the system has been properly adjusted (by comparing the two pickup fibres or two standard fibres) the system output is the ratio of the transmission of the sample to the transmission of the standard fibre. Let this ratio be "t" and the sample length be "x". Then the induced attenuation can be directly calculated from equation 1-1. The accuracy of this method is not as good as that of the next method, due to fibre coupling problems (see Chapter 3), unless two standard fibres are available to set the 100% level.

The third method compares each of the samples, including the standard, to the reference pickup fibre. This is done by connecting the reference pickup fibre to the reference detector and by connecting each sample fibre into the sample channel, starting with the standard fibre. Dividing the output from each sample by the output from the standard gives the sample to standard transmission ratio from which the induced attenuation is calculated using equation 1-1. This third method is normally used to measure the induced attenuation of damaged samples.

The remainder of the chapter will explain the functions of all of the system blocks of figure 2-1 with emphasis on the components. Discussion of noise control techniques, mode stripping, etc. will be included where applicable.

Light Source

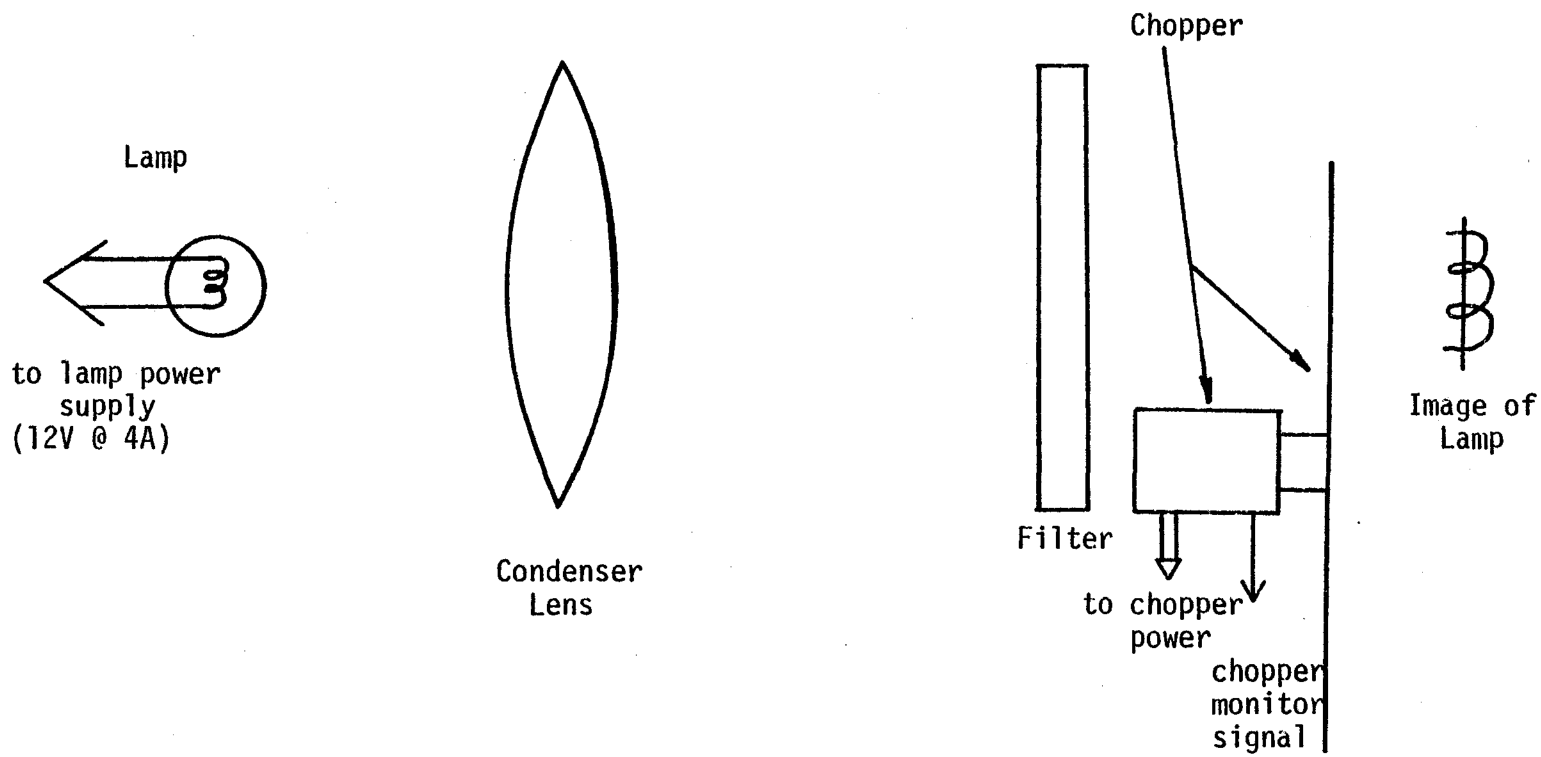
The light source is shown in detail in figure 2-2. It supplies chopped white light to the monochromator and a monitor signal, which is "high" when the chopper is passing light, to the processing electronics.

The lamp is a tungsten filament halogen cycle type which requires ≈50 W of electrical power (at 12 to 13.5 V). Its optical output in the spectral region of interest (.7 to 1.7 μm) is that of a greybody with an emissivity of approximately 0.3 and a temperature of approximately 3000 K.

The condenser lens is a 50 mm diameter, f/1 biconvex lens. In order to get as much light as possible into the monochromator, the lens must image the filament of the lamp onto the entrance slits of the monochromator. The image must be magnified by 2 to 3

Figure 2-2

Light Source



times to equal the useable height of the slit. The cone of light from the lens must also be at least f/8.6, that being the largest cone the monochromator will accept. When these two conditions are met there is no way of getting more light into the monochromator other than obtaining a brighter source, however, the amount entering the slits can be reduced by lens aberrations. To minimize the effects of the spherical aberration in the condensor lens the lens was set such that a nominal f/6 cone of light was directed at the slits. The light which passes through the edge of the lens is mostly lost since it images short of the slits but any which enters the slits is absorbed by beam stops in the monochromator.

The filter absorbs short wavelength (less than approximately 0.85 μm) light. Filtering is necessary since the second order of the short wavelength light overlaps the spectral region of interest (at the monochromator's exit slit) and would effect the transmission measurement. The filter installed is a Kodak "87C" gelatin filter. It is sandwiched between two glass plates for protection and support. The filter element has 1% transmission at 0.835 μm and 80% transmission at 0.90 μm. Mounted between the glass plates its transmission will be slightly lower. This filter is the primary factor which determines the wavelength range over which the system can be used since overlap of the second order from the grating affects the system at approximately twice the 1% transmission wavelength and the signal is too weak at wavelengths near the filter cutoff wavelength (approximately 0.85 μm). Thus the spectral range of the system extends from 0.90 μm to 1.67 μm. Other filters are available to change the spectral range as required.

The chopper produces pulses of light with a 20% duty cycle at the rate of 100 per second. The chopping is necessary since there is lower noise power near 100 Hz than at zero Hz (see preamp/detector section). Chopping the signal at "100 Hz" also makes it easy to reject signals at 60 Hz (inductive pickup) or at 120 Hz (room lights). The lifetime of the chopper motor and the accuracy of the chopper blade limit the use of higher (greater than say 200 Hz) chopping rates. The chopper motor requires a DC power supply adjustable from 6 to 8 volts which is capable of .3 A continuous output and transients in excess of 1.0 A. This power supply is also used to power part of the chopper monitor electronics (see figure 2-3). The chopper monitor produces a 3.5 V positive output when the chopper is allowing light into the monochromator. The position of the chopper blade is determined by a reflection sensor (comprising an LED and a photo-transistor). The photo-transistor and LED are positioned such that light from the LED can only be detected by the photo-transistor when a reflective object (the back of the chopper blade) is at the correct position in front of them. The reflection sensor is at the "bottom" of the chopper blade (see figure 2-3) whereas the light is chopped by the top of the blade. The blade must therefore have an even number of accurately placed chopping slots so that the optical and monitor signals are in phase.

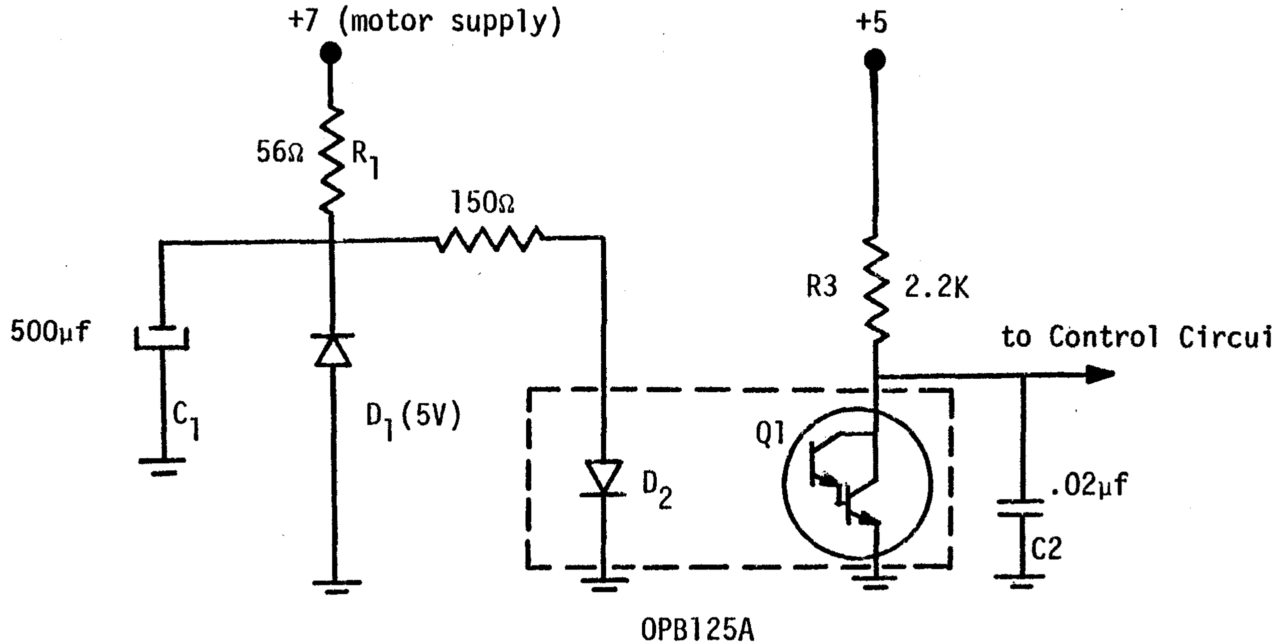


Figure 2-3

Chopper Monitor

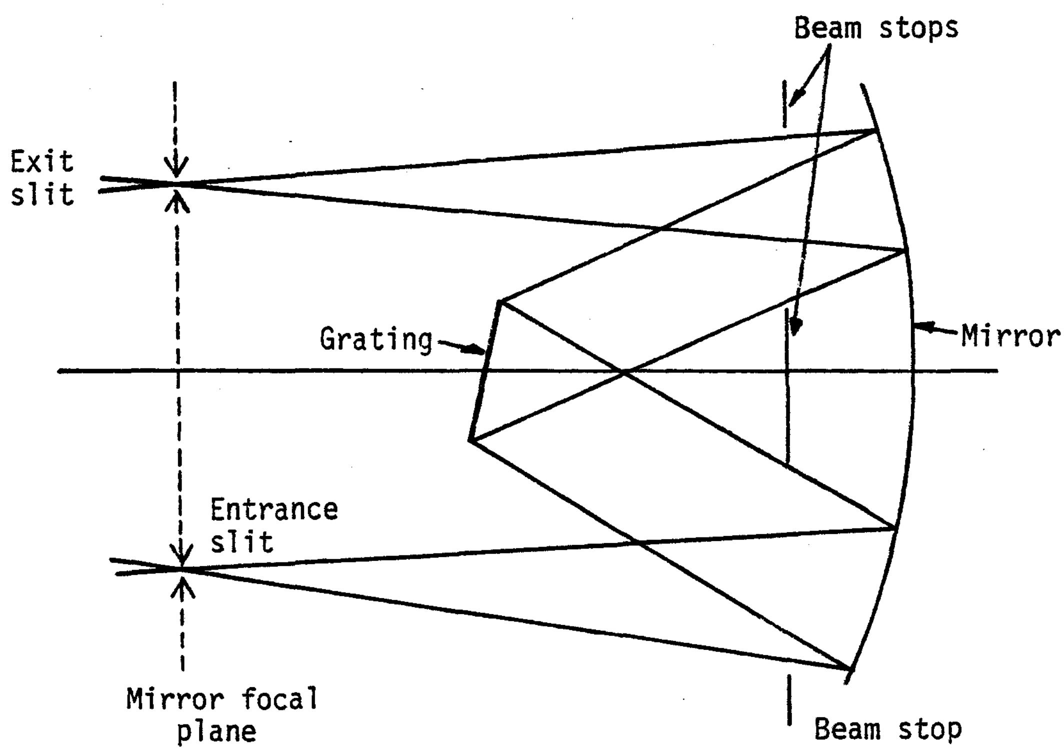
Monochromator

The monochromator is a 0.5 m Jarrel-Ash with adjustable slits (see figure 2-4). Its grating has 590 l/mm which results in a linear dispersion ($d\lambda/dx$) of 3.2 nm/mm. The slits are normally fully opened (to 400 μm) to maximize the optical throughput. At this setting the spectral width of the output light is much greater than the resolution of the instrument, therefore the output spectral width (FWHM) is the product of the slit width and the linear dispersion. For a slit width of 400 μm, which was maintained for all measurements the spectral width is 1.28 nm. This spectral width will be obtained only if the monochromator is properly illuminated which requires that two conditions be met. First the light must appear to come from a source in the plane of the entrance slit and second the light passing through the slit must fill an f/8.6 or larger relative aperture. The first condition ensures that the light incident on the grating is as well collimated as possible since the entrance (and exit) slits are on the focal plane of the monochromator's mirror. The second condition ensures that the collimated light fills the entire grating aperture to obtain the best performance from the grating.

The monochromator limits the amount of light which can get from the lamp to the fibres. If the light source has an output W (watts sterad^{-1} m^{-1} m^{-2}), the slit is "x" m wide and "y" m tall and the solid angle subtended by the f/8.6 relative aperture (or "cone"

Figure 2-4

Monochromator



of light) is "Ω" then the power passing through the exit, P, is:

$$P = W \cdot \Delta x^2 \cdot \Delta y \cdot (d\lambda/dx) \cdot \Omega \qquad (2\text{-}1)$$

Thus the power passing through the monochromator is proportional to the square of the slit width. This can be seen intuitively since the output power is linearly proportional to both the entrance slit width and the spectral width. Since the spectral width is linearly proportional to the exit slit width (which is equal to entrance slit width) the output power is proportional to the slit width squared. The percentage of the output power coupled into a fibre depends on both the output adaptor and the fibre.

Output Adaptor

The output adaptor is required to transfer the light from the monochromator output slits into the pickup fibres. This process is complicated by the requirement that all core modes in the fibres must be excited in order to properly measure the fibre attenuation. To excite all of the core modes the cone of light entering the fibre must fill the NA of the fibre. The f/# of the cone required to fill the NA is given by:

$$f/\# = \frac{1}{2}\sqrt{\frac{1}{(NA)^2} - 1} \qquad (2\text{-}2)$$

$$\simeq \frac{1}{2(NA)} \qquad (2\text{-}3)$$

The NA of a typical silica fibre is between .1 and .3 thus an f/5 to f/1.6 cone is required. The output adaptor converts the f/8.6 cone of light coming from the monochromator into a lower f/# by using a lens to produce a demagnified image of the exit slits. This is shown schematically in figure 2-5. The f/# of the light on the image side of the lens is increased by the same factor as the image is demagnified. The NA of the cone on the fibre (image) side of the lens, NAo, is:

$$NAo = 1/\sqrt{1 + (2M(f/\#))^2} \qquad (2\text{-}4)$$

$$\simeq 1/(2Mf/\#) \qquad (2\text{-}5)$$

where: f/# is the f/# of the monochromator (f/8.6)

M is the demagnification factor (see figure 2-5)

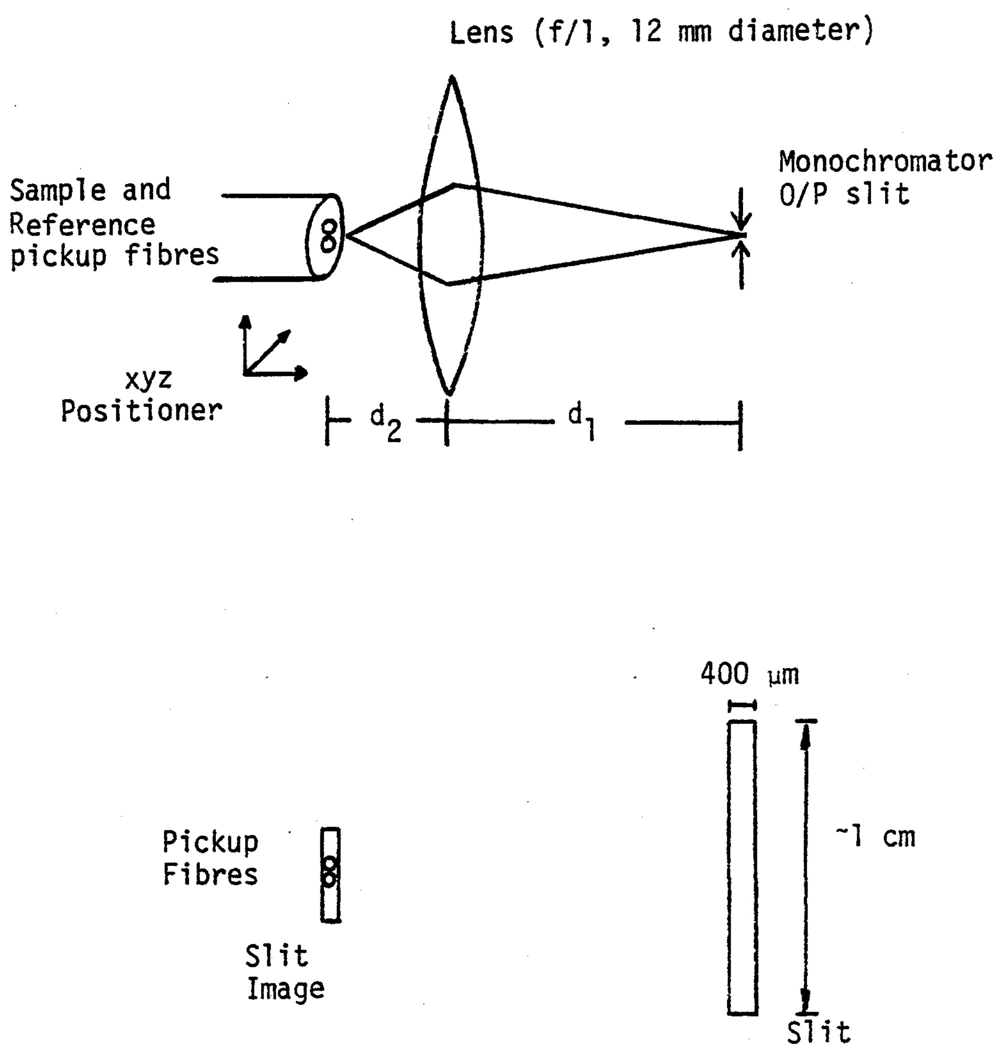
For example to match BNR 319 fibre with an NA of .20 a demagnification of 3.5 is required.

Matching of the fibre f/# to the monochromator f/# also ensures that as much light as possible is being coupled into the fibre. For most fibres the image of the slit will be wider than the fibre core and in this case overfilling of the fibre NA, by demagnifying the image more than necessary, will ensure that all modes are excited with no loss of signal. This assumes that the effects of lens aberrations are small, which is reasonable since the image is expected to be 100 μm wide.

Since the image is wider than the (expected) fibre core a simple 3 axis fibre positioner is used to position the two pickup fibres at the image point. The image is approximately 20 times taller than it is wide so the pickup fibres must be aligned with the long axis of the image and be reasonably close together to

Figure 2-5

Output Adaptor



Magnification $M = d_2/d_1$

receive as much light as possible. Proper alignment of the fibres with the long axis of the image also ensures that chromatic aberration will affect both fibres equally and will be cancelled.

The pickup fibres are the same type of fibre as the sample to obtain the best coupling match. They are cemented in a plastic or metal holder which is held by the 3 axis positioner. Since the positioner has no rotation axis the holder must be sufficiently long (50 mm is adequate) that it sticks out of the positioner and can be rotated to align the fibres with the image. The ends of the pickup fibres in the holder are polished flush with the face of the holder.

Pickup fibres are used to collect the light from the monochromator output instead of using the sample fibre and a reference fibre for two reasons. First it would be difficult to position the sample and reference fibres correctly and repeatably on the image of the slit. Since the pickup fibres do not move during the course of an experiment this problem is largely avoided. Secondly, it is possible to "mode scramble"the pickup fibres, to ensure that all modes are excited, without affecting the accuracy of the measurement. The process of mode scrambling involves straining the fibre (i.e. by bending it) to cause light to be coupled from one mode to another. It is particularly effective at populating high order modes which would not be populated if the NA of the fibre was not filled. Mode scrambling would only be used if the output adaptor could not fill the fibre's NA since scrambling causes some light to be lost from the core.

The pickup fibres used to test the system were typically one or two metres long. The results in a recently published paper[4] suggest that the length of the pickup fibres should be at least an equilibrium length so that the light launched into the fibres being tested has an equilibrium mode distribution. The attenuation measured using this latter method better approximates the attenuation of a long fibre despite the short sample. The pickup fibre length should therefore be increased to say 500 m from 1 or 2 m.

Mode Stripping

Since the image of the slit is approximately one fibre diameter wide, considerable light also enters the cladding of the fibre. Many fibres have jackets with a low index which allows the light to propagate down the fibre cladding. Although the loss for these cladding modes is relatively large, for samples of 10 to 100 metres, the cladding modes could introduce a significant error in the attenuation. The cladding modes are therefore stripped by contacting the cladding with a fluid of equal or slightly greater index so that the light in the cladding leaks out into the liquid and is lost. Approximately 5 cm of linear contact between the cladding of BNR 319 fibre and microscope immersion oil removed the cladding modes. For a given oil the required contact length depends on the index mismatch. It can be measured by increasing the length of cladding in contact with the oil by a centimetre at a time while observing the signal generated by the light leaving the end of the fibre. When increasing the contact length fails to decrease the signal, there is adequate contact. For this test to be effective the test fibre should not be mode stripped on either side of the test area. The pickup fibres are therefore unsuitable as they are at least partially mode stripped by the epoxy in the fibre holder. Mode stripping must be performed at the detector end of the sample to remove light scattered or leaked from the core into the cladding as well as light initially launched into the cladding. The sample should also be stripped at the entrance end to reduce the chance that the large amount of light coupled into the cladding will reach the detector. Mode stripping is conveniently carried out by painting oil onto a bare horizontal fibre. Although pure glycerin is an effective mode stripping fluid for silica clad fibres, it is hygroscopic and absorbed water will eventually decrease the index of glycerin to the point where it is less than that of the silica.

Connection of Test Fibres

Sample and reference fibres are connected to the sample and reference pickup fibres by either butting the fibres together or by fusion splicing the fibres. The other ends of the sample and reference fibres are butted to the appropriate detectors. The relative merits of these coupling arrangements are discussed in Chapter 3.

Detectors

The detectors and associated preamps are mounted in a light tight metal box to reduce electrical and optical noise pickup. The fibres enter through holes in front of the detectors. The fibre rests on a magnet on the outside of the box and is held in place by a steel block which is placed on top of the fibre and is attracted to the magnet. Both the magnet and the steel block are covered with felt to avoid pinching the fibre and to exclude room light from the box.

The sample and reference detectors are lead sulphide (PbS) photoconductors (Quantum Detector Technology type QDIE). The PbS active layer and associated metal contacts are sandwiched between two .25 inch square glass slides and epoxied to a "TO-5" header. The pair of detectors are mounted by their headers in an aluminum holder which supports the detectors and equalizes their temperatures.

Fibres are coupled to the detector by butting against the detector's glass cover plate. The fibre ends are held against the detector by pushing them against the detector such that the fibre is slightly bent. The steel block holds the fibre in position. Each fibre is positioned laterally on the detector surface by small aperture mounted immediately ($\simeq$1 mm) in front of the detector. Index matching oil is used at the fibre-detector interface to reduce scattering and reflection caused by imperfections on the fibre end or the detector surface.

The spectral responsivity of both detectors was found to vary across the active area. The apertures which position the fibres in front of the detectors must be positioned so that the illuminated area of both detectors has the same spectral responsivity. This is discussed in more detail in Appendix B.

Preamps

The schematic for preamps is given as figure 2-6. The detector load resistors and bias voltage filter are located on the same circuit board as the preamps. The 100 V bias supply is filtered by R4 and C3. Since the signal and reference channel preamps are of the same design only the upper preamp in figure 2-6 will be explained. Here R5 is the detector load resistor. The signal developed across the detector as a result of the change of its resistance due to absorption of light is amplified 1000 times by IC1 and associated components. High frequency noise (greater than 1.2 KHz) is filtered out by R9 and C5. IC2 and associated components further amplify the signal. The gain of IC2 (and IC4) are set so that the peak signal in the reference channel is 13.5 V. This requires a gain of two for BNR 319 fibre. The gain is set by changing R10. C6 and R13 filter out noise of 5.8 Hz or less.

Signal to Noise Ratio

The signal to noise ratio (SNR) of the sample and reference signals is determined by the detectors and the preamp as the signals leaving the preamp are much larger than the noise output of the components in the processing electronics. Noise is added to the

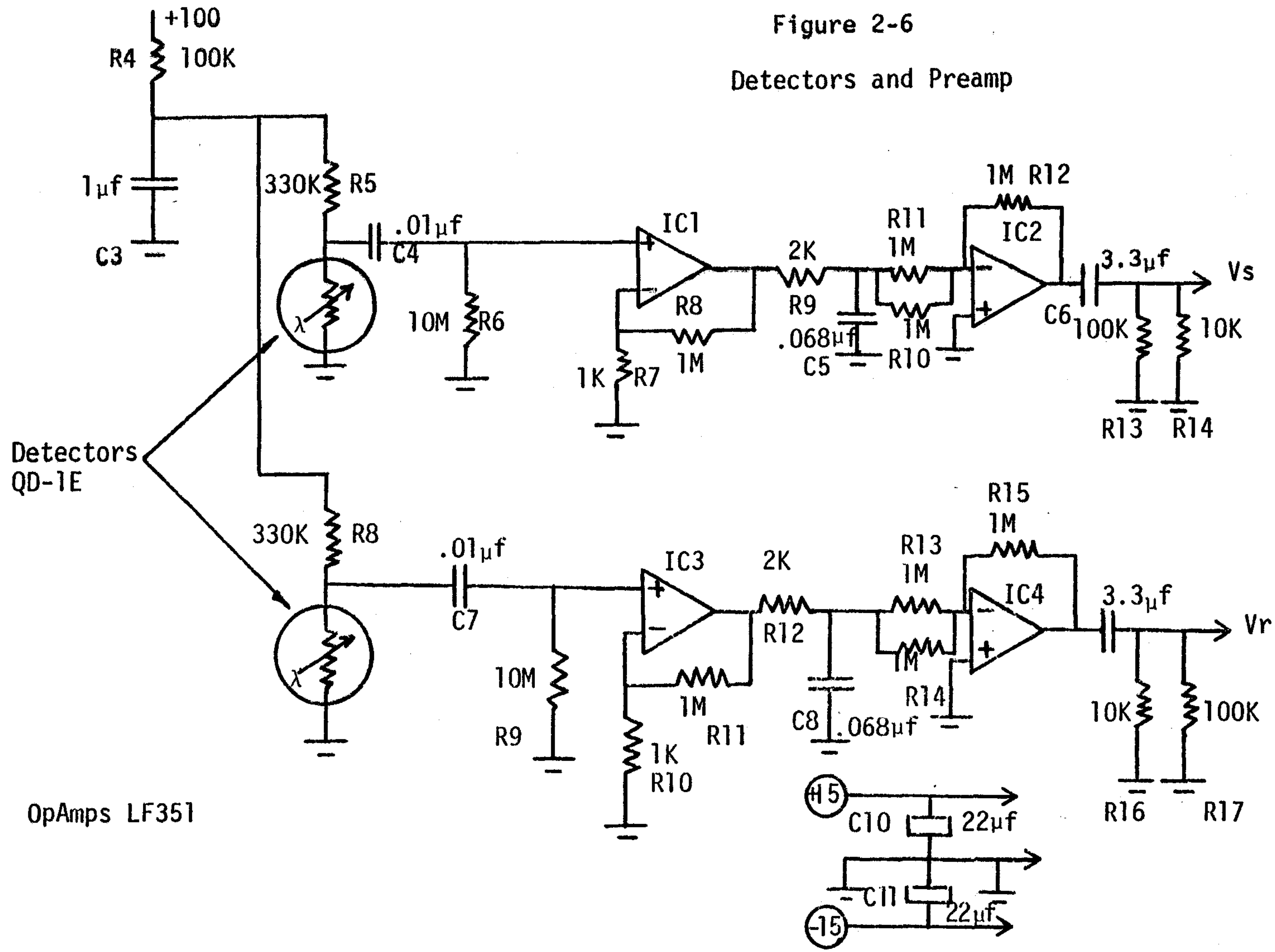


Figure 2-6

Detectors and Preamp

signals from many sources. There is thermal noise generated by the detector resistance and the preamp resistors, shot noise on the detector bias and photocurrents, noise generated by the operational amplifiers and noise from stray light or electrical interference. There is also "1/f" noise generated by resistances and operational amplifiers. Measurements of the noise at the preamp output showed that the "1/f" noise is negligible at frequencies in excess of 100 Hz hence the chopping rate must be at least 100 sec^{-1}. No electrical and optical pickup could be detected at either 60 Hz or 120 Hz. The majority of the noise at the preamp output (greater than 90%) is shot noise on the detector bias current. The remainder of the noise is the thermal noise generated by the resistances, including the detector and load resistor, and the operational amplifiers. Experiment also verified that the SNR of the detectors is independent of the bias voltage, once the bias is sufficient that the detector noise exceeds the other noise sources, for bias voltages up to 100V. Excessive bias will reduce the SNR according to the manufacturer. Thus there appears to be no method of significantly increasing the SNR by changing the preamp or bias supply. Other methods are discussed in Chapter 4.

The preamplifier bandwidth has been left very wide (5.8 - 1200 Hz) to avoid distorting the signals, which would reduce their amplitudes. The sampling circuit in the processing electronics shifts the noise and signal frequencies making it easier to build a filter to separate the signals from the noise after the sampling operation.

The exception is the low frequency noise (less than approximately 5 Hz) which must be removed before sampling.

While no 60 or 120 Hz noise could be detected (with the preamp box properly closed) there were occasional spikes of noise which are believed to be of electrical origin. This noise could sometimes be avoided by working at night. Since this noise occurs as occasional spikes it does not normally reduce the range of the system as does a "steady" noise source.

The wide band (5.8 to 1200 Hz) noise output of the preamp is 50 mV RMS for a preamp gain of 2000.

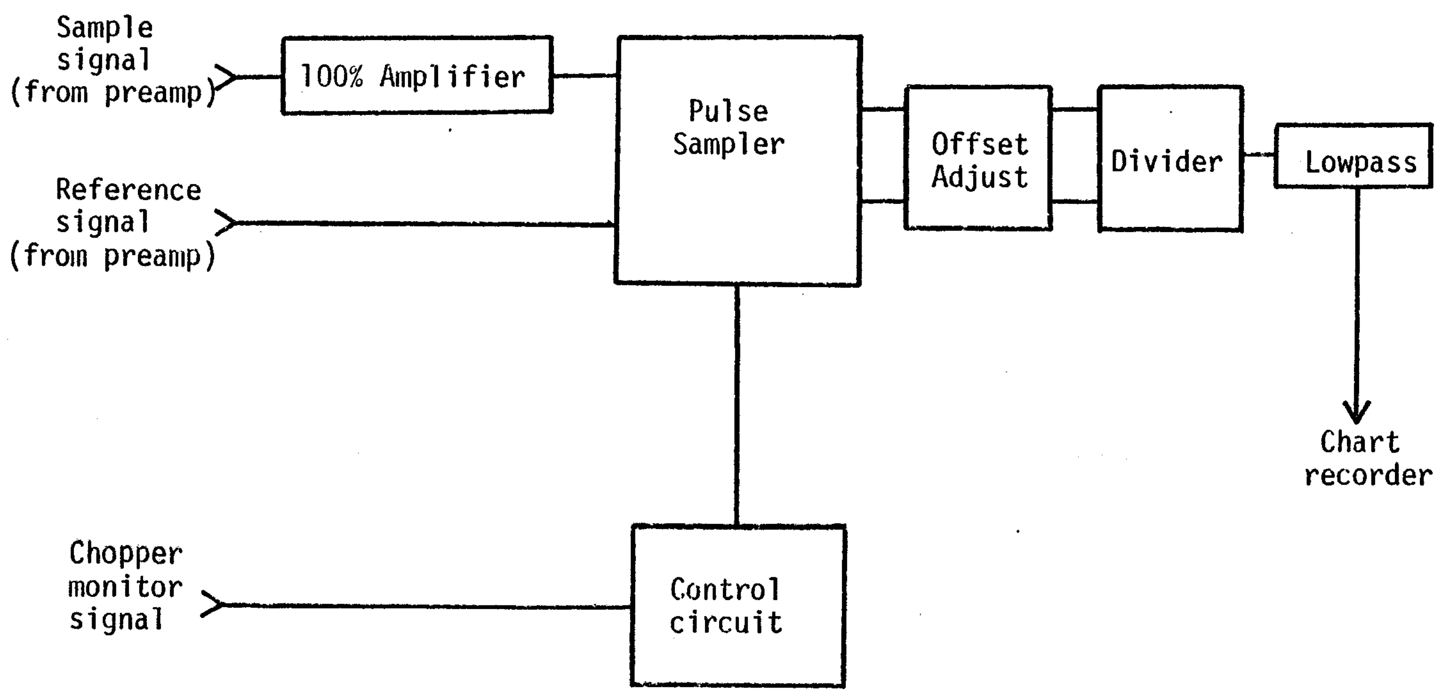
Signal Processing Electronics

The signal processing electronics is required to convert the sample and reference signals into an output compatible with a chart recorder. Figure 2-7 is a block diagram of the system. The operation of the complete signal processing section is discussed next. Following this is a description of each of the circuits in more detail.

The "100% set amplifier" amplifies the sample signal as required to set the 100% level on the chart recorder. The "pulse sampler" simultaneously samples the sample and reference signals at their peaks. The sampling is controlled by the "control circuit" which is triggered by the chopper monitor signal. The samples are stored by "holding" capacitors for 10 msec, i.e. until the next samples are taken. The output of the hold capacitors

Figure 2-7

Signal Processing Electronics



are DC levels which are 80% of the peak to peak signals plus a certain amount of noise. The DC levels are then filtered to remove most of the noise by selectable RC time constant. The offset and scale adjust circuit corrects any offset of the sample level by subtracting a fraction of the reference level and amplifies the sample signal by a calibrated, selectable gain to change the full scale output from 100% to 20% etc. The sample and reference outputs of the offset adjust circuit go to the divider circuit which outputs the ratio of the sample and reference signals. The "lowpass filter" is a second order filter which removes some of the noise which passed through the RC filters in the pulse sampler. Either the "transmission" output from the divider or the low pass filter can drive a chart recorder.

Noise Control Methods

The sampling and filtering determines how much of the noise present at the preamp output is allowed to reach the chart recorder. The sampling process is particularly important as sampling shifts the frequencies of the signals and the noise. The signals are shifted from 100 Hz to DC. After the sampling, the (DC) signal can be filtered, with no distortion, by a simple low pass filter. The RC filter used to filter the signal has a 3 dB bandwidth ranging from .15 to 1.5 Hz. Because of the aliasing[5] effect of the sampling operation, noise at integer multiples (including zero) of 100 Hz are shifted to zero frequency. Thus sampling and filtering circuits exclude all noise except that within ±1 filter bandwidth of integer multiples of 100 Hz. The preamplifier removed the large "1/f" noise component near zero Hz and noise at frequencies greater than 1.2 KHz before it reached the sampling circuit. The bandwidths of the preamp and RC filter are specified by their 3 dB points and are first order filters. The lowpass filter following the divider circuit further attenuates noise near the edge of the preceeding filter's pass bands.

The divider circuit divides the sample level by the reference level and multiplies the result by ten. The noise on the sample and reference levels are combined by the divider. The output of the divider, T, is given by:

$$T = 10\left(\frac{S + S'}{R + R'}\right) \tag{2-6}$$

where S - sample level

S' - sample noise

R - reference level

R' - reference noise

Since R' << R, T is approximately given by:

$$T \approx 10\left(\frac{S}{R} + \frac{S'}{R} - \frac{SR'}{R} - \frac{S'R'}{R}\right) \tag{2-7}$$

Since S' and R' are normally much smaller than R the term containing S'R' need not be considered. The noise input to the divider is determined by the gain of the preamp (and the 100% set amplifier) and the filter bandwidths but not by the signal or reference levels. Therefore the noise reaching the chart recorder will increase as the reference level is reduced and will also vary with the signal level.

Circuits Comprising the Processing Electronics

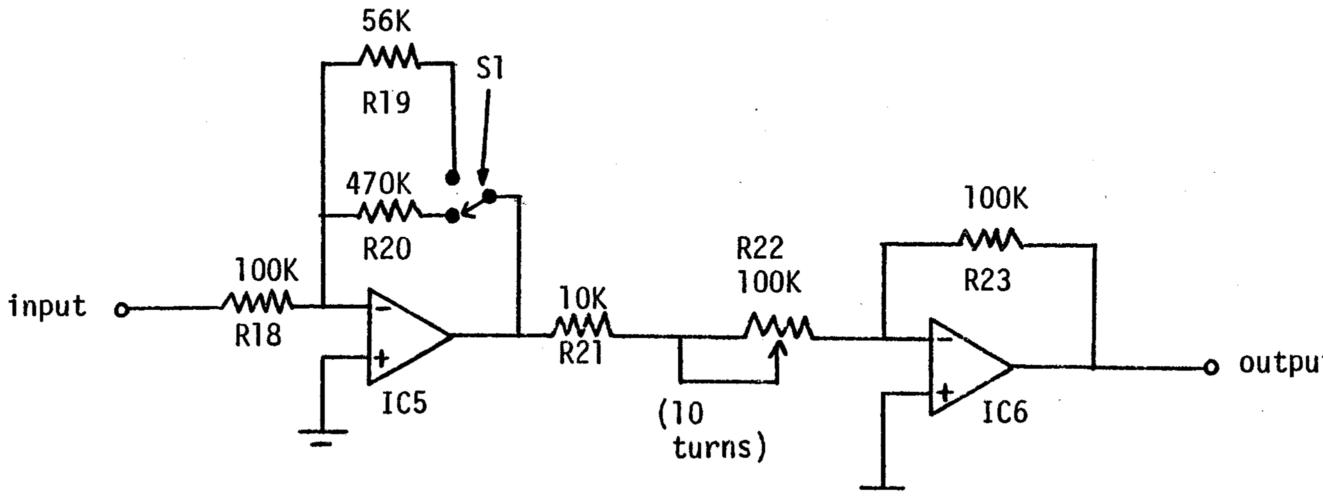
The schematic of the 100% set amplifier is shown in figure 2-8. It is used to set the peak system output to full scale (10 V) when comparing for example an undamaged fibre to a reference fibre. This is done by amplifying the sample signal. The gain of the amplifier is determined by the settings of S1 and R22. It can be set to any value between .51 and 47 times.

The pulse sampling circuit schematic is given as figure 2-9. The pulse sampler comprises two sample and hold cricuits and a dual selectable RC time constant. The sample and hold circuits simultaneously sample the sample and reference signals at their peaks and hold the sample for 10 msec, until the next sample. The RC time constants filter the output of the sample and hold circuit.

The pulse sampling circuit has two identical channels, its operation will be explained for the upper channel only. IC7 and D3 accurately rectify the signal, allowing only the positive going peaks to pass through. This is required since IC9, C10 and C11 should not be reverse biased. IC8 buffers the rectified signal to charge the hold capacitor through IC9A, when transmission gate IC9Ais "opened" by a sample pulse from the control circuit. IC10 is a high input impedance buffer which prevents charge leaking from C10. S2A, C11, R28, R29 and R30 comprise the selectable time constant. The time constant can be set to 0.0, 0.1, 0.33 or 1.0 second or it can be left open to disconnect the offset and scale adjust circuit from the divider.

Figure 2-8

100% Set Amplifier

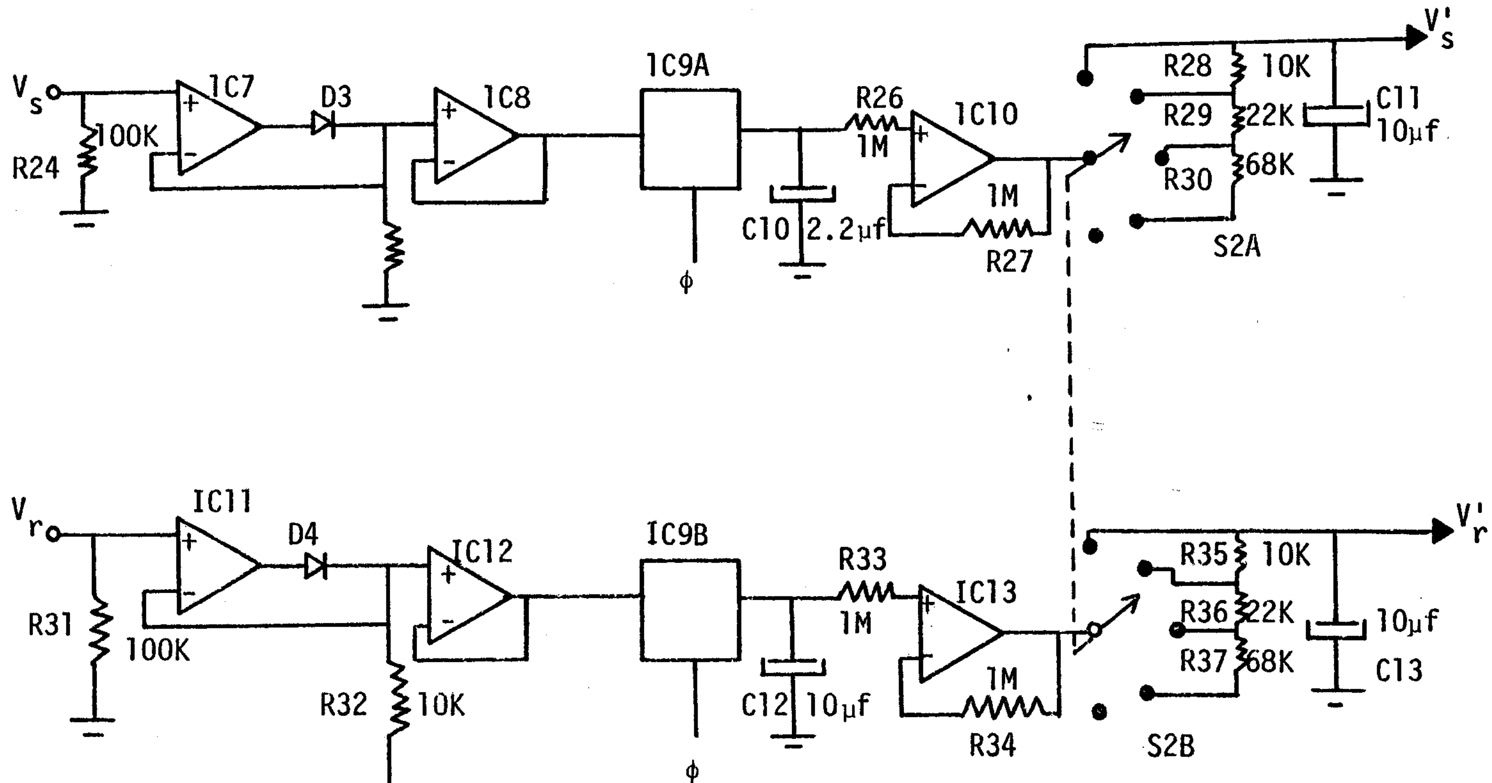


IC5 & IC6 LF356

15V supply bypassed at each
amplifier with .1μf

Figure 2-9

Pulse Sampling Circuit



IC9 - CD4016

IC7,8,11,12 - LM301A (27 pf compensation)

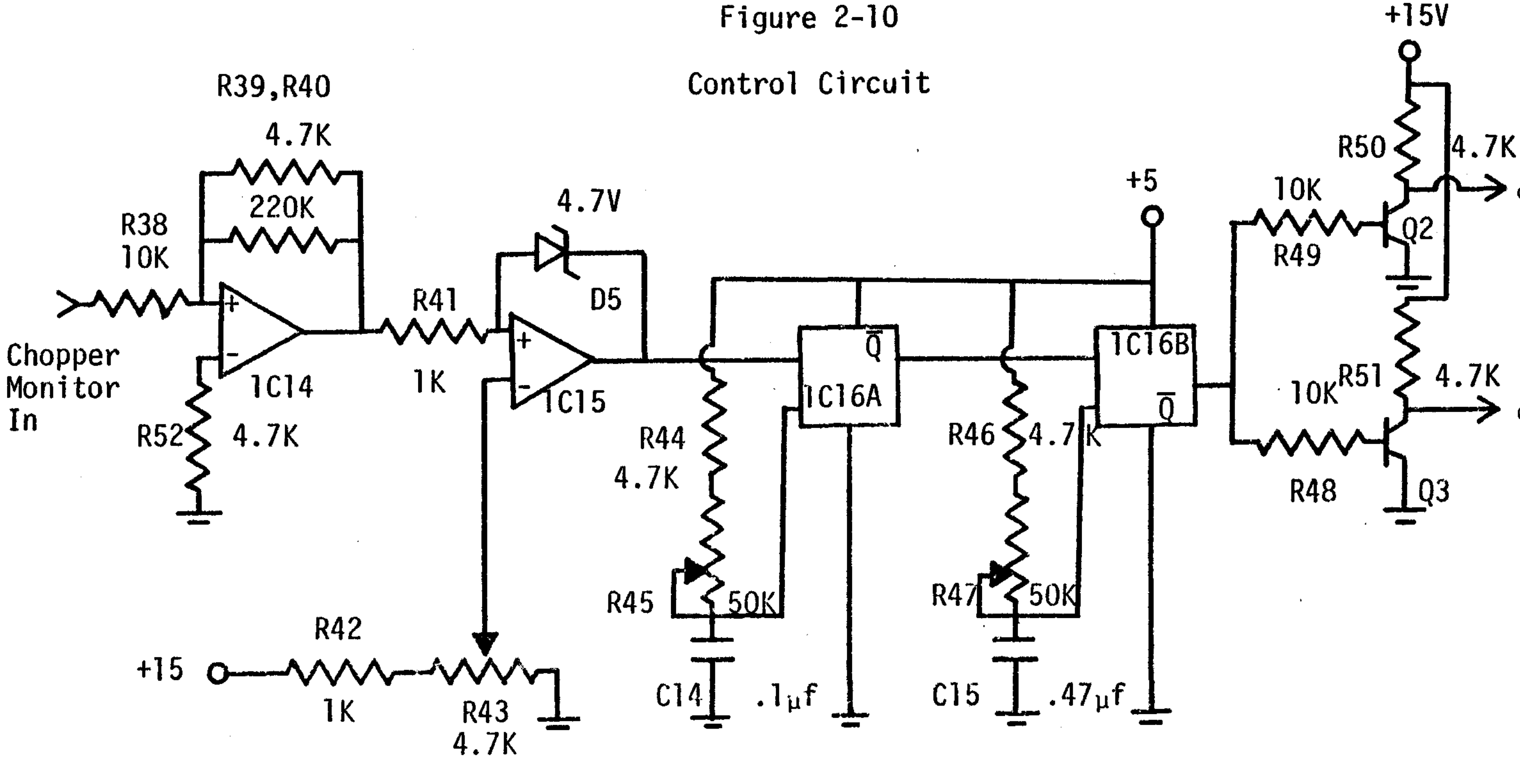
IC10,13 - LF351

The control circuit takes the output from the chopper monitor and converts it to sampling pulses suitable to drive the pulse sampling circuit. The schematic of the control circuit is given in figure 2-10. The output from the chopper monitor, a positive going pulse of approximately 3.5 V, is inverted and scaled by IC14. When output of IC14 is greater than the constant output of R42 the output of IC15 goes to +5 V and triggers IC16A. The "Q" output of IC16A falls to zero for a period determined by R44, R45 and C14. This period allows the sampling to be finely adjusted to coincide with the signal peaks. When the output of IC16A rises back to +5 V, IC16B is triggered and its Q output falls to zero for approximately 1 msec. This 1 msec pulse is the sampling pulse. It is inverted and amplified to 15 V, as required by the pulse sampling circuit, by Q_2 and Q_3.

The schematic of the offset and scale adjust circuit is given in figure 2-11. This circuit offsets the sample level by an adjustable fraction of the reference level. It also multiplies the offset sample level by a calibrated factor of 1, 2, 5, 10 or 20 to set the full scale output to 100, 50, 20, 10 or 5 percent respectively. The sample is offset by subtracting a fraction of the reference from it. The fraction of the reference to be subtracted is set by R60. The subtraction is done by IC18. IC21 multiplies the sample signal by a gain factor which is determined by S3 and its associated resistors.

Figure 2-10

Control Circuit

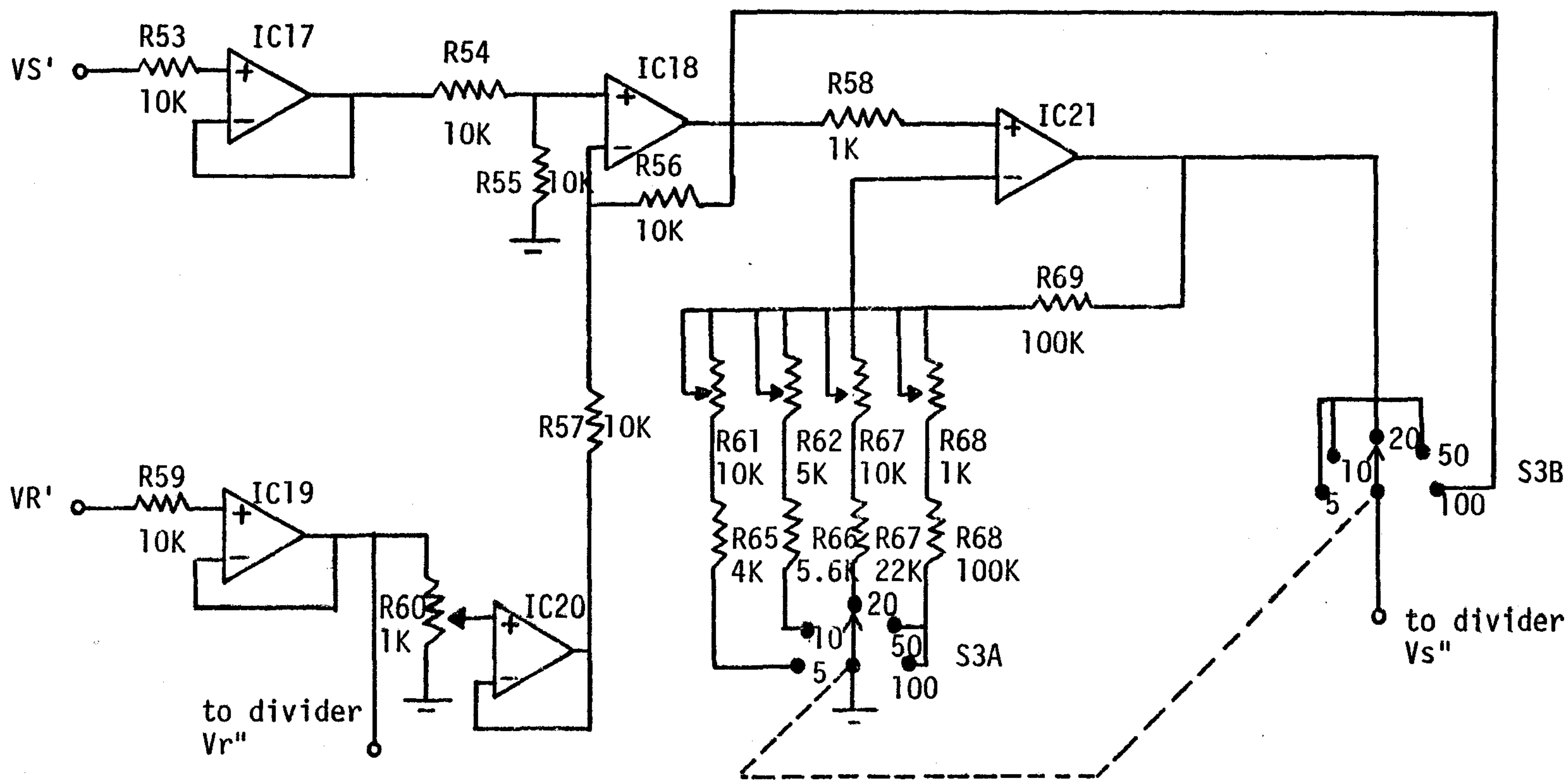


1C16 74123

opamps LM301A

Figure 2-11

Offset and Scale Adjust



All opamps LM301A

The offset can be used in conjunction with the scaling circuit to expand say the 90% to 100% transmission range to full scale (0 to 10 V) on the chart recorder.

The schematic of the divider circuit is given in figure 2-12. This circuit finds the ratio of the sample and reference levels (the transmission) or one minus the ratio of the sample and reference levels (the absorption). IC24 and IC25 perform the division. The output of IC25 is 10 Volts when the sample equals the reference. IC26 buffers the transmission output and IC27 subtracts the transmission from 10V to get the absorption. More detail on IC24 is found in reference 6.

The schematic of the low pass filter is given in figure 2-13. It is a second order low pass filter designed to reduce the noise equivalent bandwidth of the .1 sec RC filter. It has a 3 dB frequency of 1.4 Hz (equivalent to a .1 sec time constant). Details on modifications to the circuit, which would be required to obtain maximum effectiveness for longer time constant filters, can be obtained from reference 7.

The schematic of the power supply is given in figure 2-14. The supply provides regulated outputs of 15 V and 5 V for the electronics as well as the 100 V detector bias. Standard three terminal regulators are used except for the 100 V supply which uses a zener diode. S4 is the power switch for the entire unit. S5 turns off only the input to the detector bias supply (to avoid possible damage to the preamplifier when its cover is removed with the main power on).

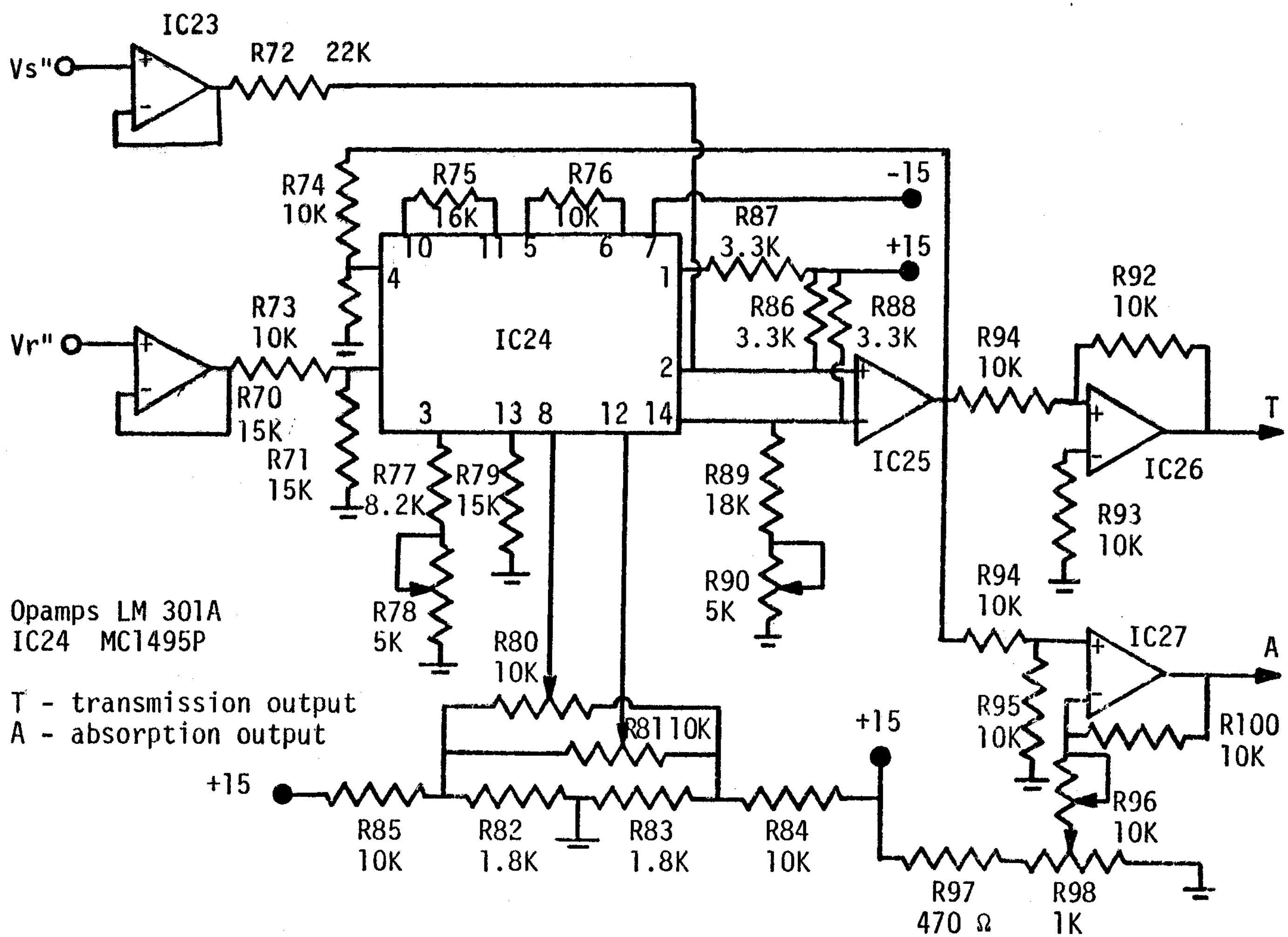
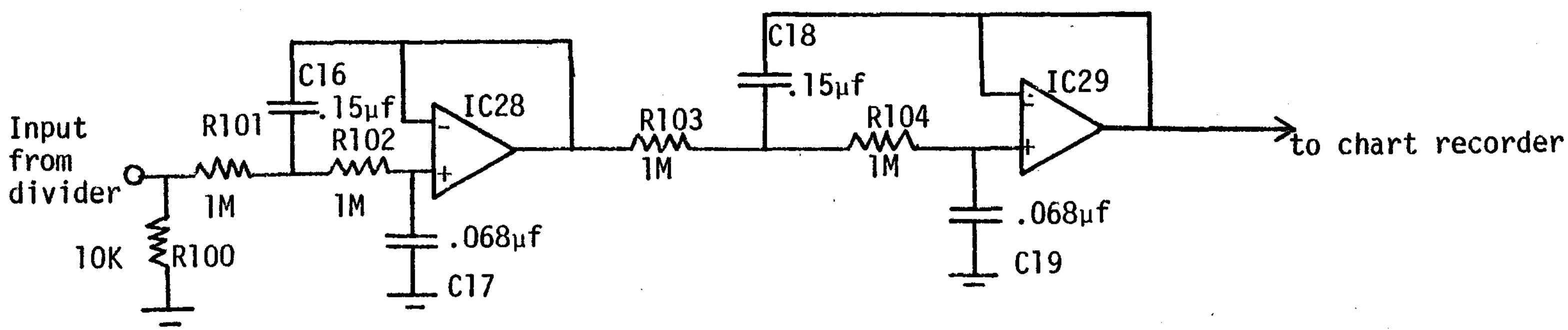


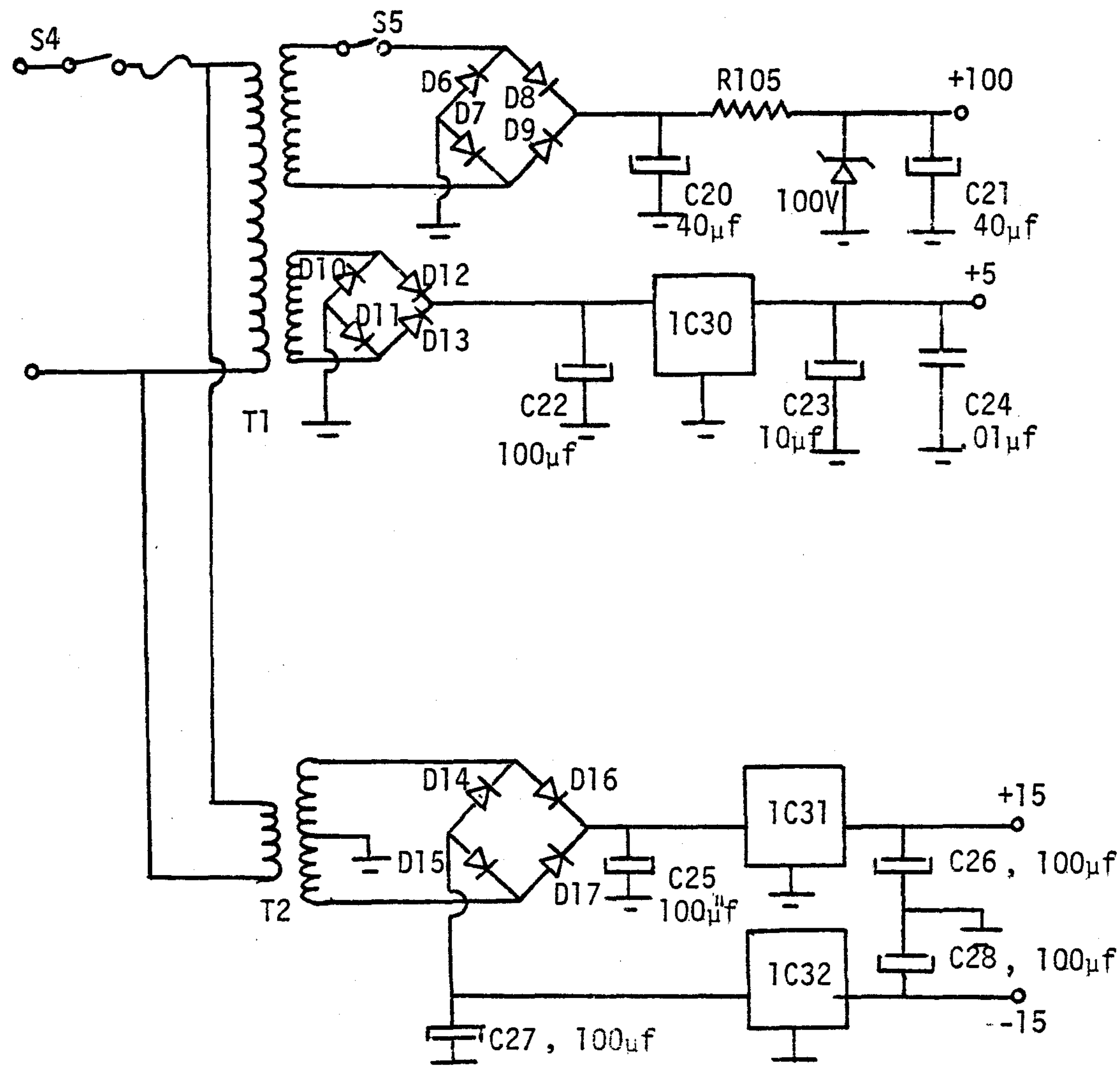
Figure 2-12
Divider

Figure 2-13

Low Pass Filter



Opamps - LM351



Power Supply

Figure 2-14

CHAPTER 3

SYSTEM PERFORMANCE

In this chapter the performance of the fibre transmission measuring system will be analyzed. The measured values of system noise, coupling repeatability and electronic non-linearities are given. The bounds on system performance are derived and discussed.

Wavelength Range

One of the basic parameters of the system is the wavelength range over which the transmission can be measured. There are two factors which determine this range, the reference signal level and the wavelength where the second order of shorter wavelengths transmitted by the installed light source filter overlaps the wavelength being tested.

The reference signal level determines the shortest wavelength which can be measured since as the reference level falls off both the signal to noise ratio and the accuracy of the electronics (discussed later) are reduced. The reference level is determined by the output of the lamp, the transmittance of the optics including the monochromator, the filter transmittance, the reference fibre's transmission and the responsivity of the detectors, all of which are functions of the wavelength. The measured variation of reference level with wavelength is shown in figure 3-1. The rapid rise in

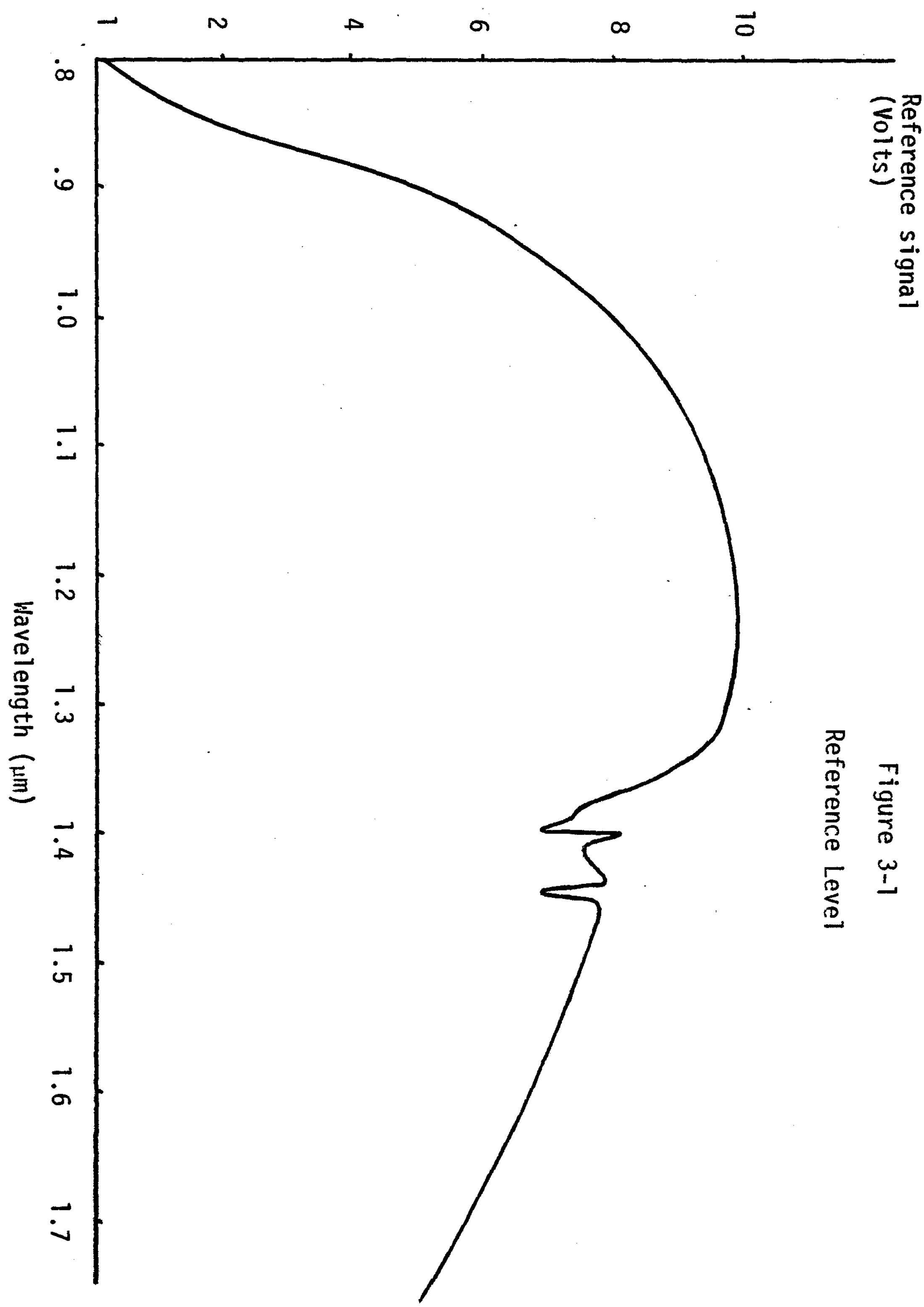


Figure 3-1
Reference Level

reference level between .8 and .9 μm is primarily due to the light source filter. The lower limit of the wavelength range is approximately .9 μm. The exact value depends on the lowest SNR which can be tolerated. The upper limit of the wavelength range is twice the wavelength at which the filter has 1% transmission (.835 μm) since at this point the second order has a significant effect. The upper limit on the wavelength range is approximately 1.67 μm for the Kodak 87C filter.

Also visible in figure 3-1 are fluctuations in the reference level near 1.4 μm. These fluctuations are believed to be related to the OH absorption often seen in fused silica fibres and optical components. The only noticeable effect of these fluctuations on the system output are several small "spikes" of approximately 2 divisions (of 100) amplitude. These are believed to be caused by a slight misalignment of the pickup fibres. The wavelength region covered by the system is therefore .9 μm to 1.67 μm with limited accuracy near 1.4 μm. Since there is usually a large absorption in silica fibres near 1.4 μm the lower accuracy in this region will not normally be a problem. The wavelength range is primarily determined by the filter in the light source and can therefore be altered by changing the filter.

Linearity of the Electronics

One of the major factors which could limit accuracy of the transmission measurement is the accuracy of the electronics. The only part of the electronics with a measurable inaccuracy was the divider circuit. The measured error in the divider circuit, as a percentage of output, is given in figure 3-2. This curve was found to remain the same over a period of several weeks. It will, however, change drastically if the divider is recalibrated (see Appendix B). Since the error remains constant for a reasonable period, the divider non-linearity can be corrected for by using the information in a curve such as figure 3-2. For this reason figure 3-2 is plotted as a percent of output. Knowing the output voltage and reference voltage enables the operator to correct the errors in the output. The error, however, increases so rapidly below one volt that it is not really practical to correct the error, switching to another scale (say 10% full scale) is a better solution. The reference voltage can be plotted as a function of wavelength for any given set of conditions. Factors which determine the reference voltage were listed previously. None of these may be changed without replotting the reference versus wavelength curve.

Wavelength Resolution

The wavelength resolution of the system is another important parameter. It is primarily determined by the monochromator dispersion and the slit width. A slit width of 400 μm was used to maximize the signal. All measurements were made with the 400 μm slit width. Since the dispersion for the 590 l/mm grating is 3.2 nm/mm, the resolution of the monochromator is 1.28 nm. The system resolution could be degraded by several factors. The light source must be properly

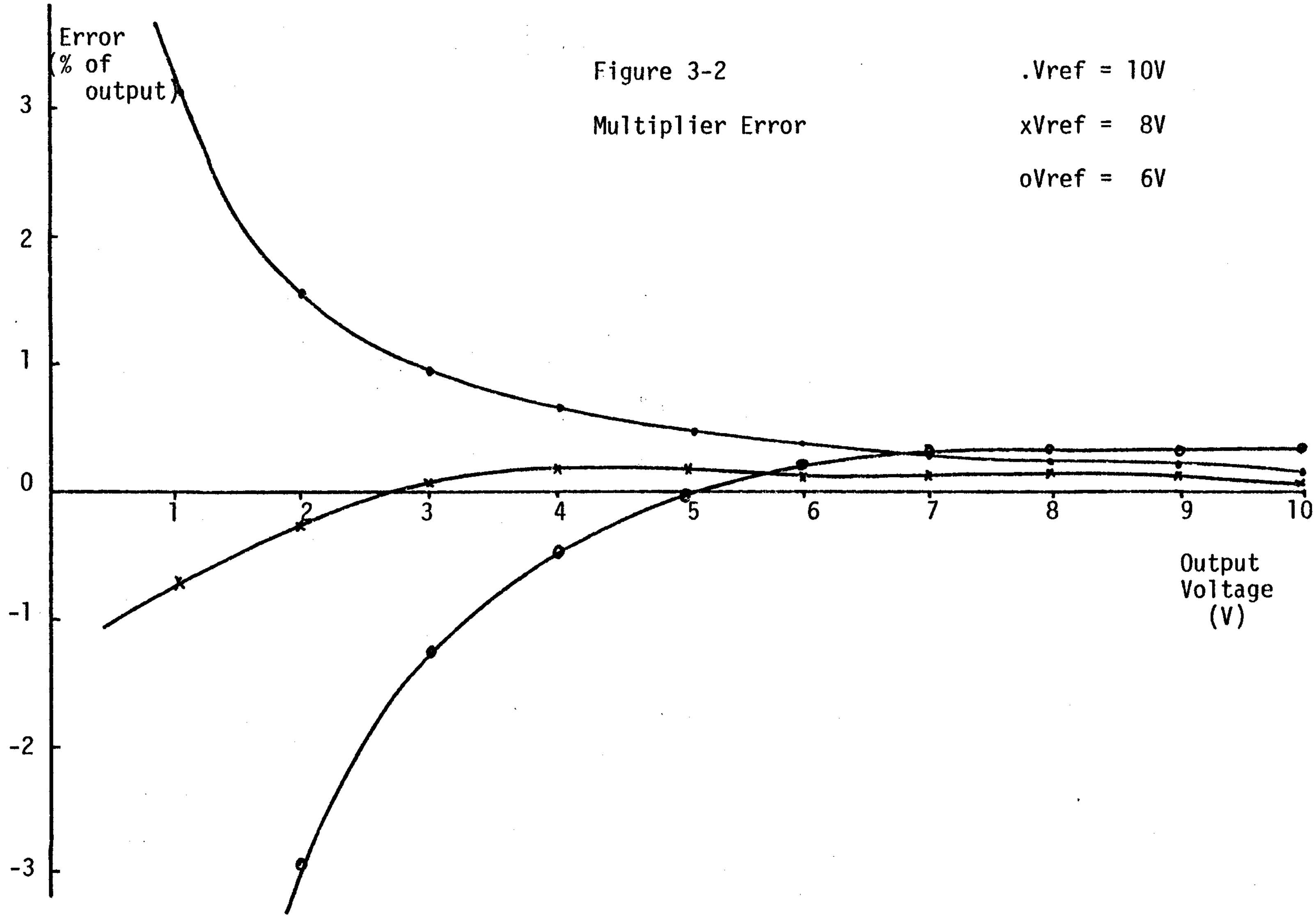


Figure 3-2

Multiplier Error

adjusted (see Chapter 2 and Appendix B) to ensure that the resolution of the monochromator is not degraded. The speed at which the monochromator is scanned through the wavelength range must be slow enough that the time constant of the electronics does not integrate the signal thereby degrading the resolution. As a criterion to determine the maximum scanning speed it is reasonable to use a rate equal to the wavelength resolution (1.28 nm) per four time constants (four time constants being approximately the time required for a capacitor to charge to 99% of a step input). Thus for a .1 sec time constant the maximum scan rate is 1950 Å/min. Because the actual scan rate is twice that marked on the monochromator (since the grating has 590 l/mm not 1180 l/mm) this corresponds to a scan rate of roughly 1000 Å/min on the monochromator.

Minimum Sample Transmission

The minimum transmission which the system can measure is determined by the accuracy requirement and by the signal to noise ratio since, as the loss is increased the SNR is decreased and width of the chart recorder trace increased. The width of the output trace limits the accuracy possible in reading the output. A trace width of 1 division peak to peak (of 100) was chosen as the maximum allowable since near this width the noise limited the accuracy of reading the output more than did the chart paper.

The minimum transmission was determined by simulating a large loss. This was done by pulling the sample fibre away from the detector while comparing the sample to the reference. The "full scale" switch was used to maintain the output near 100%. The scale which increased the output trace width to one percent was recorded for all three time constants using BNR 319 pickup fibres. The minimum transmission which can be measured is 10% of the full scale (since below 1 volt the multiplier is very non-linear). For example with a .1 sec time constant the trace width was 1% on the 20%scale so the minimum transmission which could be measured is 2%. Thus the total allowable sample loss is 17 dB. The total allowable loss for .33 and 1.0 sec time constants was 20 and 21 dB respectively. Although this method is subjective it provides a good indication of the maximum sample loss.

The above values hold only for BNR 319 fibre. The maximum loss for other fibres can be estimated by estimating how much light is coupled into them relative to the 319 fibre. The amount of light coupled in is roughly proportional to the square of the core radius and the square of the NA. Dividing the minimum transmission by the relative coupling (the ratio of the light coupled into the new fibre to that coupled into the BNR 319) will give an estimate of the minimum transmission for the new fibre (this follows from eqn. 2-7).

Drift

Drift of the output also limits the system accuracy. This is probably due to very low frequency noise and the effects of temperature changes on the electronics and fibre holders. The drift was measured by recording the output every five minutes for an hour. Two tests were performed. For the first test only the chopper motor was turned off between measurements. For the second test the chopper, lamp and detector bias were turned off. The system was allowed to cool for over 30 minutes before starting either test.

In both cases the output steadily declined during the first 3 minutes changing about 1%. It is expected that this is the results of the divider chip warming up as this chip is known to be temperature sensitive and normally runs warm to the touch. After the first three minutes the drift was approximately ±0.25% peak at an output of 6 V. The tests were carried out in an airconditioned room where the temperature was apparently constant. Attempts to simulate a different temperature by blowing compressed air into the electronics box and on the divider in particular failed to produce a noticeable change, but this test could not be considered conclusive.

The system, therefore, requires approximately three minutes to warm up and can be expected to drift up or down by about 0.25%. Turning off the lamp, chopper and bias voltage does not appear to increase the drift.

Sample Positioning

There are two allowable methods which can be used to measure the radiation damage. These are termed the "on-line" method and the replacement method. In the on-line method a sample fibre is attached to the system and its spectral transmission is scanned repeatedly while the fibre is being (slowly) damaged. This method is the most accurate since the sample does not need to be removed between measurements and fibre coupling problems are eliminated. The on-line method cannot easily be used for long term studies of annealing. The long term damage can be checked by using the replacement method. The replacement method requires that the fibres be connected into the system, measured and removed from the system. The accuracy of this method is therefore affected by the repeatability of the fibre coupling. Also when replacement is used to study a set of fibres of a particular type, with varying degrees of damage, the fibres must have the same core size or the coupling repeatability will be further degraded. Since core diameter tends to change monotonically along the fibre length all samples in the set should be cut consecutively.

In the tests which were done to check the coupling repeatability a sample fibre was connected between the sample pickup fibre and the detector. It was always compared to the reference pickup fibre only. All butt joints in these tests used index matching oil to reduce the effect of Fresnel reflections and scattering from the fibre ends which are never perfectly flat and square. Fibres used in the tests were acceptable only if the end was very close to being flat across the entire core and most of the cladding. An 80 power sterio microscope was used to inspect the ends. The only defect which was allowed was the presence of a small chip on the side of the cladding which makes the end appear like a "D". The opposite defect, where a piece of cladding protrudes from the surface is absolutely unacceptable as is a fibre where the end is curved or at a definite angle with respect to the side, since all of these cause a gap between the affected fibre and another surface. The fibres were mode stripped, as discussed in Chapter 2, at the joint with the pickup fibre and just in front of the detector.

Two methods of connecting sample fibres to pickup fibres, the butt joint and the fusion splice, were tested.

A butt joint is made by nearly butting the two cleaved fibre ends together with only a thin film of index matching oil between the ends. The joint is made by fixing one fibre and manoeuvering the other using a three axis positioner. The operator must observe the fibres through a microscope while positioning them to adjust the separation of the fibre ends.

The equipment used to hold and manoeuver the fibres, called the "jig", must not allow motion of one fibre relative to the other due to reasonable levels of environmental influences such as vibrations, air currents and temperature fluctuations. The positioner is used to move one fibre laterally with respect to the other to maximize the system output and therefore the transmission of the joint.

The jig which was used for the experiment consisted of a three axis positioner fitted with standard .001 inch micrometers, two V-grooved steel blocks and a baseplate. One V-grooved block was fastened to the positioner, the other to the base plate. Fibres were held in the V-grooves by felt covered magnets. The positioner was adequate for the job but "touchy", a differential screw micrometer would be easier to use.

A fusion splice is done by fusing two fibres together with an oxygen-butane torch. The fibres are butted together with enough pressure to cause one of the fibres to bend to one side. The fibres are then melted together. When melted the fibres tend to align themselves, thus the jig need not be as precise as that used for the butt joint.

The jig used for the fusion splices consisted of a baseplate, a pair of prealigned V-grooves on a "U" block and a positioner (microscope adjusting rack and pinion). One fibre is attached to the positioner and alides freely in its V-groove. The other fibre is held firmly in its V-groove. The fibres are pushed together using the positioner and fused using the torch. The joint is reheated several times to obtain maximum transmission.

The two methods were tested by running a number of trials for each. The output of the system, measured by a digital voltmeter, was recorded for each trial. The average, standard deviation and the deviation of the extreme results (called the maximum and minimum errors) are given in table 3-1. The standard deviation, maximum and minimum error are listed as a percent of the mean value for ease of comparison, since the mean value was changed between experiments.

The results given in table 3-1 indicate that the butt joint is the more repeatable method of coupling. Considerably more skill

TABLE 3-1

FIBRE TO FIBRE JOINT TEST RESULTS

	Butt Joint	Fusion Splice
Number of trials	5	6
Mean output	7.00	6.00
Standard deviation	0.5%	2.9%
Maximum error	+1%	+4%
Minimum error	-0.8%	-5%

TABLE 3-2

FIBRE TO DETECTOR JOINT TEST RESULTS

	Sample Cleaned only	Sample Cleaved
Number of trials	10	10
Mean output	5.72	6.94
Standard deviation	1.5%	1.9%
Maximum error	+1.5%	+3%
Minimum error	-2.0%	-2.8%

is required for the fusion splice and possibly more practice would reduce the standard deviation of the trials. The number of trials was limited by the length of time and length of fibre required to get an acceptably cleaved end. When cleaving tools become less expensive and less sensitive to fibre diameter changes they could reduce the effort in obtaining good ends. The accuracy of both methods could be improved by trying each joint several times to determine the best coupling and then obtaining a joint very close to the best previous result. The residual error could be removed by noting the difference between the best and current calues and correcting the output by this factor.

Using the above method it should be possible to keep the error in the butt joints within ±1% (two standard deviations) and possibly within ±0.5%. The above method would definately reduce the error in the fusion splices although it is not certain that they would equal the quality of the butt joints.

The fibre to detector joint was tested by running a number of trials where the sample fibre was freshly cleaved and where the sample was cleaned but not cleaved. The results of the experiments are given in table 3-2. The repeatability of the cleaned ends is better than that of the freshly cleaved fibres however cleaving does not seem to make a large difference. The fibre to detector butt joints have much poorer repeatability than the fibre to fibre butt joints. This is believed to be a result of the responsivity of the detector being non-uniform and may be related to the spatial variation of the spectral responsivity mentioned in Chapter 2.

The effect of having a different spectral responsivity of the illuminated areas of the sample and reference detectors is to cause the "reference line" (i.e. the output obtained by comparing the sample and reference pick-up fibres) to be slanted. If the slope on the reference line is small and repeatable it is cancelled when normalizing the results for a damaged and undamaged sample. The repeatability of the slope was tested by measuring the slope a number of times. Between each measurement the end of the sample fibre was cleaned by not cleaved. The slope is defined as the change in output between .9 and 1.5 μm divided by the output at 1.2 μm.

The average of the five values of the slope was .057, the standard deviation of the values was .0017 (3% of the average) and the peak errors were +11% and -5.3% of the average. The standard deviation (.0017) is equivalent to an error of 1% at .9 μm and 1.5 μm (relative to 1.2 μm).

The error in coupling the fibre to the detector is thus made up to two parts, the coupling error at any one wavelength and the slope error across the spectrum. Twice the standard deviation of each set of errors will be used as an estimate of the error for the purpose of assigning system bounds. The errors due to the coupling and slope are assumed independent so that the errors can be added in RSS (root of the sum of the squares) fashion. Thus the total error for coupling of fibres to the detector is ±3.6% when the sample fibres are only cleaned and ±4.4% when the sample fibres are cleaved.

The above errors were measured for one type of fibre (BNR 319) and would probably be different for other fibres particularly if the core size was significantly different.

The total error in coupling a sample into the system is the above error for the fibre-detector joint combined with the fibre to fibre (butt joint) coupling error of ±1%. Adding these errors in RSS fashion gives a total error of ±3.7% (cleaned only) or ±4.5% (recleaved). The total error in measurement can be taken as the above value since the drift and error remaining after the divider is corrected are too small to be significant. With reasonable care the ends of the samples should not require cleaving after the first installation so the error in measurement can be taken as ±4% (±3.7% rounded up).

The measurement accuracy determines the minimum sample length (for ±1 dB/km accuracy). The SNR determines the maximum measurable sample attenuation for a given fibre. The minimum sample length and maximum sample attenuation are plotted in figure 3-3 for a measurement error of ±4% (as discussed above), a time constant of 0.33 seconds and a wavelength of 1.2 μm. A sample with an attenuation and length which falls below the diagonal line and to the right of the vertical line (as indicated by the cross-hatched area) can be measured to better than ±1 dB/km. Thus for a measurement error of

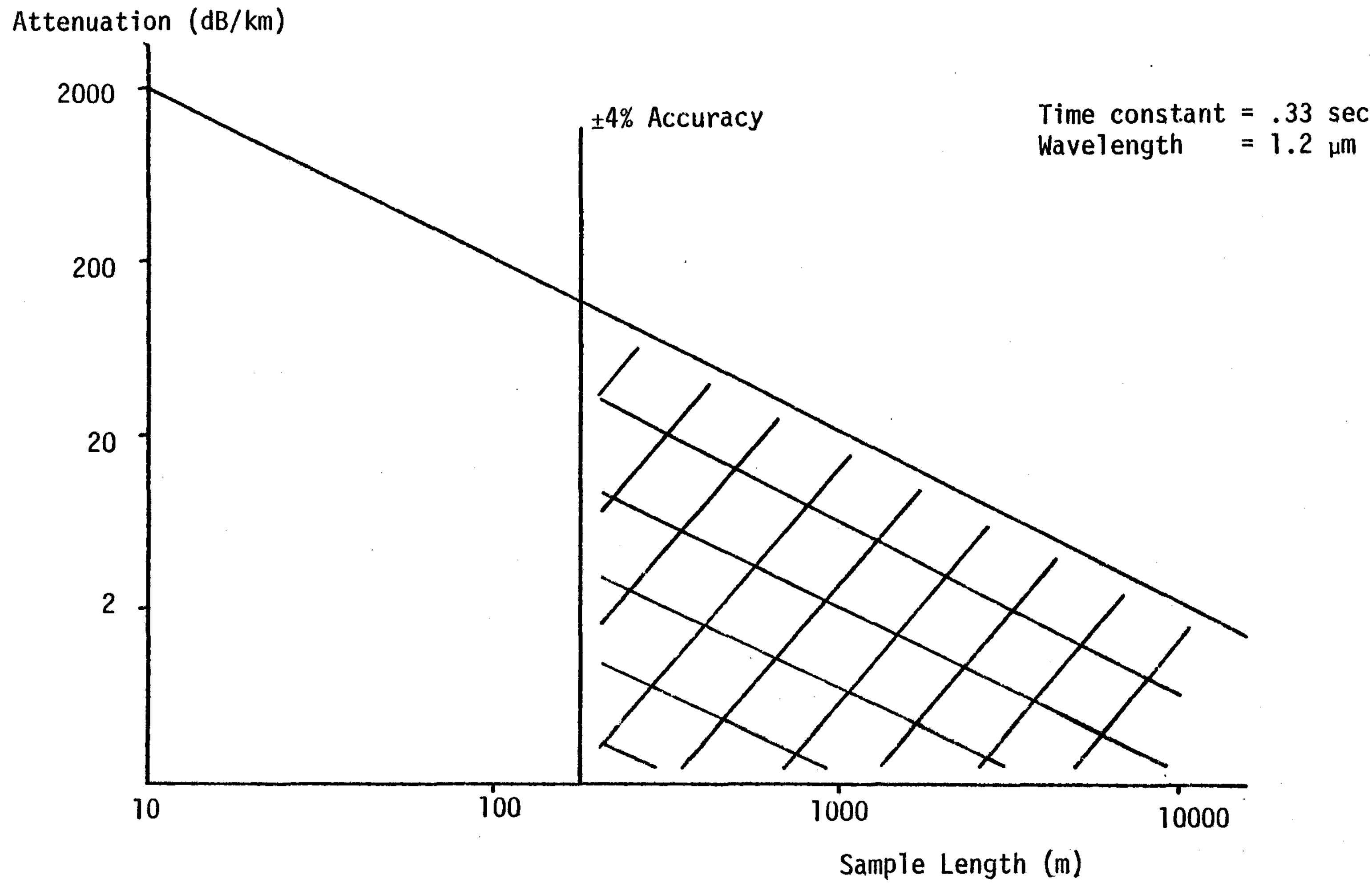


Figure 3-3

Measurement Boundaries

±4% the samples must be at least 175 m long and have an attenuation of less than 115 dB/km. At .9 μm and 1.65 μm the maximum sample loss is reduced from 20 dB to 17 dB and 18.1 dB respectively due to the lower sample and reference levels at these wavelengths.

One method of improving the measurement accuracy is to leave a short fibre held in place on the sample detector. The sample fibre would be butted to the short fibre on the detector at one end and to the sample pickup fibre at the other end. Thus the measurement error would be the RSS sum of two 1% errors or approximately ±1.4% error. This would reduce the required sample length to approximately 60 m. The required sample length for ±1.4 and ±4% measurement errors are plotted in figure 3-4. Also shown in figure 3-4 are the maximum attenuation lines corresponding to all three time constants.

To this point the attenuation accuracy has always been ±1 dB/km. Figure 3-5 shows the required measurement accuracy versus sample length for ±1, ±5 and ±25 dB/km attenuation accuracy. For a measurement accuracy of ±1.4% the ±1, ±5 and ±25 dB/km attenuation accuracies require samples of 60, 12 and 2.4 metres.

Figure 3-5 shows how the sample length can be traded off against the accuracy of the attenuation measurement for a given transmission measurement accuracy. However, for attenuation accuracies on the order of ±1 dB/km the required sample length is at least 60 m (as discussed above) due to the measurement accuracy (at best ±1.4%). To test shorter samples to ±1 dB/km the measurement accuracy must be improved. Similarly the maximum attenuation which the sample can have is approximately 115 dB/km with a time constant of 0.33 sec or 120 dB/km

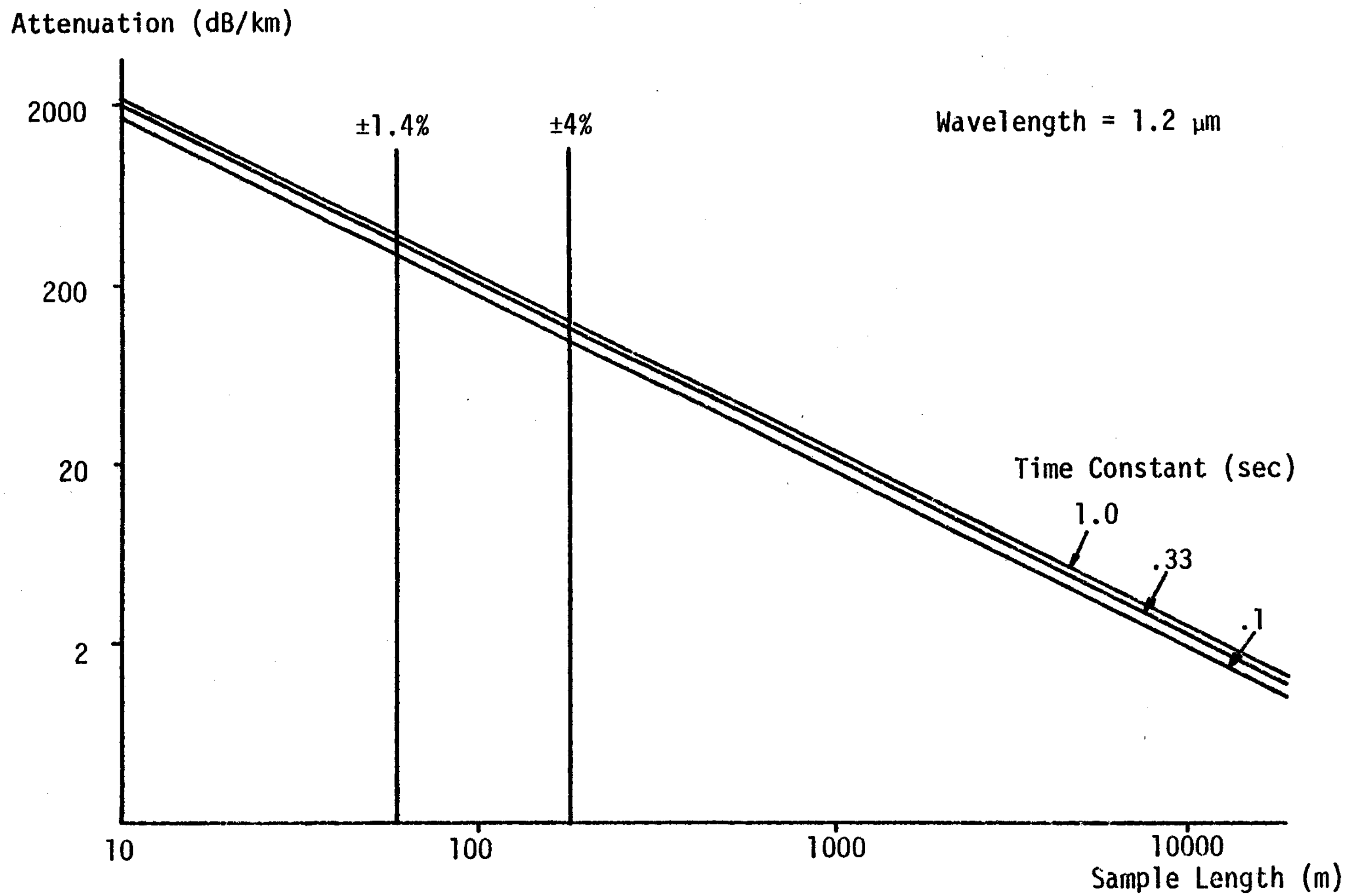
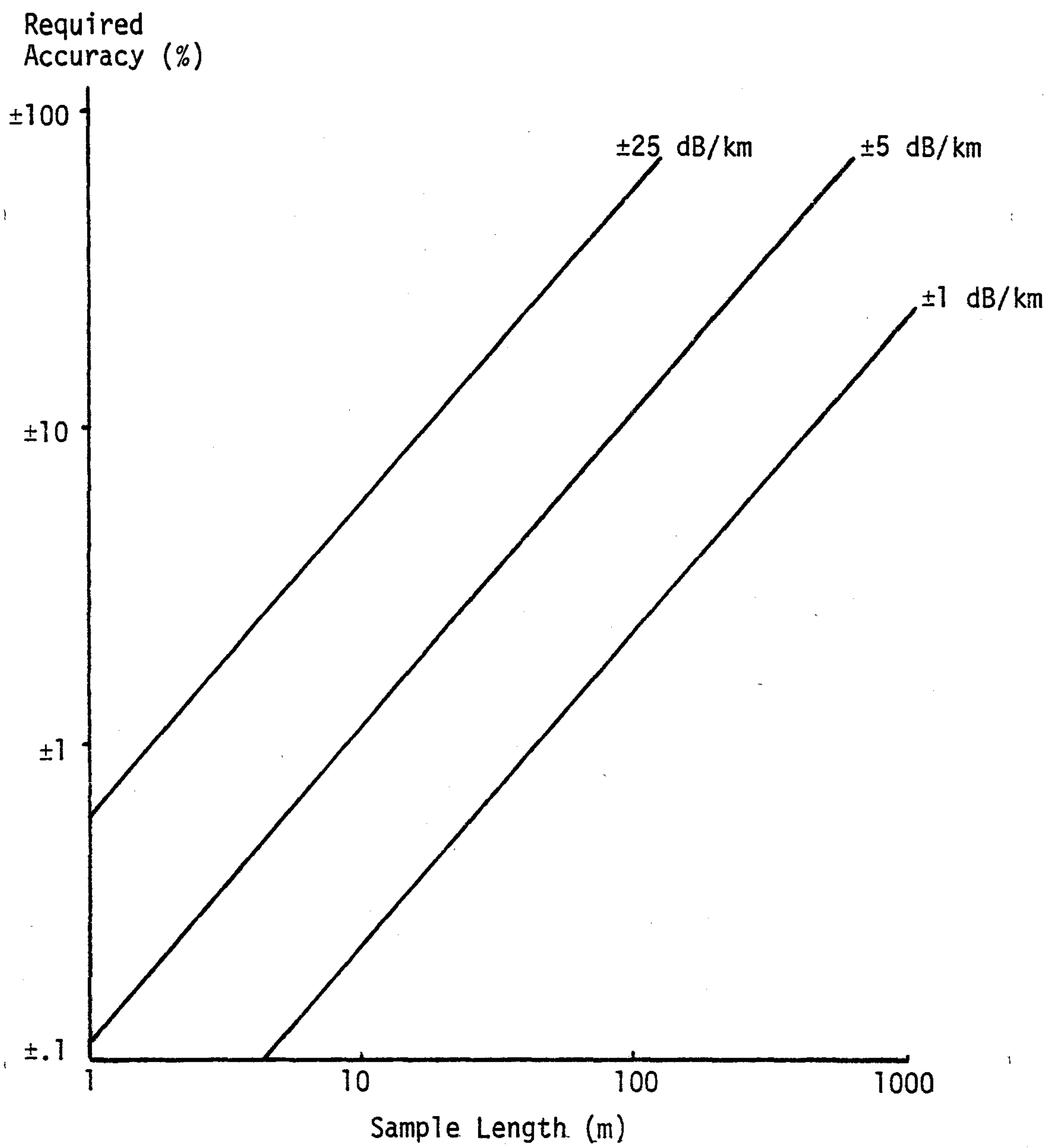


Figure 3-4 Measurement Boundaries for
±1.4% and ±4% Accuracy

Figure 3-5



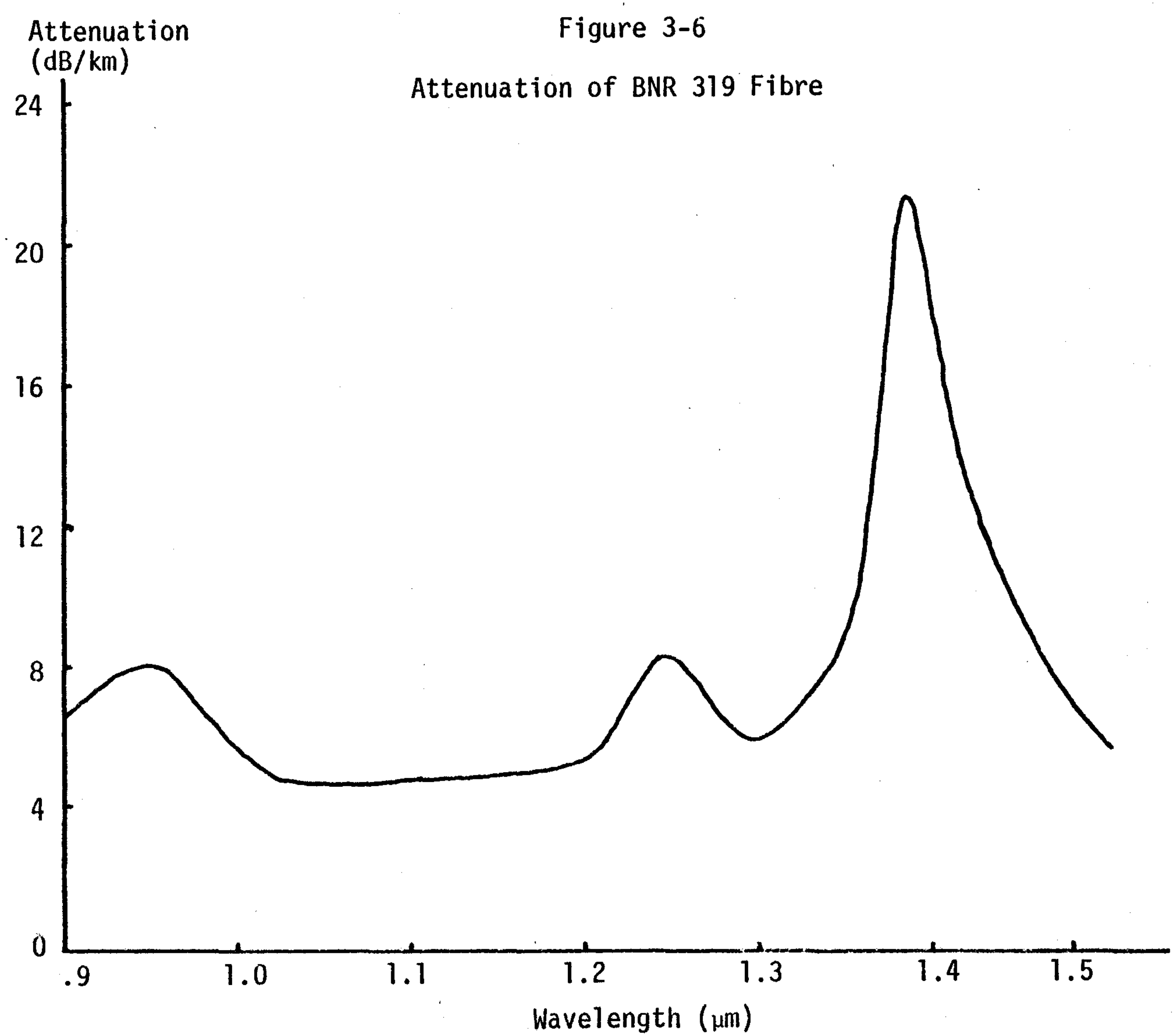
Required Accuracy Versus
Sample Length

with a time constant of 1.0 seconds. Improving this for a given fibre requires that the SNR be increased. Whether the measurement accuracy or SNR should be improved depends on whether shorter samples or higher attenuations are to be studied. Other methods of increasing the measurement accuracy and the allowable sample loss are discussed in the next chapter.

The system was used to measure the transmission of a 125 m sample of BNR 319 fibre (undamaged) by the long/short method. The sample was compared to the reference pickup fibre only. The sample was measured and the short length cut about 1 m from the detector without disturbing the detector butt joint. The 1 m piece was then measured. The transmission of the long fibre is the ratio of the output of the entire sample to the output from the short piece of the sample. This was converted to attenuation and is plotted in figure 3-6. Since the detector butt joint was not disturbed the accuracy of this measurement is approximately ±1% which results in an attenuation error of less than ±1 dB/km for a 125 m sample. The attenuation of the BNR 319 fibre is given as 6 dB/km at .83 μm which agrees well with the 6.5 dB/km measured at .9 μm.

Figure 3-6

Attenuation of BNR 319 Fibre



CHAPTER 4

CONCLUSIONS

The major limitations on the transmission measuring system are the 17 to 21 dB maximum sample attenuation, determined by the signal to noise ratio, and the minimum sample length of 60 m, determined by the measurement accuracy. These limitations are for BNR 319 fibre and must be calculated for any other fibre type as described in Chapter 2. They also apply only at 1.2 μm. The maximum sample attenuation is 3 dB lower at the short wavelength end of the system range (.9 μm) and 1.9 dB lower at the long wavelength end of the range (1.65 μm).

Improvements to the system can be made in 3 ways. These are increasing the signal, reducing the noise and increasing the repeatability of the fibre coupling. These methods are discussed below as is the accuracy which could be expected by using the "on-line" method of attenuation measurement instead of the "replacement" method which has been discussed to this point.

Measurement Accuracy Improvements

The measurement accuracy is primarily determined by the repeatability of the fibre coupling. One method of reducing this error, leaving a fibre positioned on the detector and butting other fibres to it instead of the detector, was discussed in Chapter 3.

While this should result in a significant decrease in measurement error, better results should still be possible at the detector-fibre interface. One method which should help is to hold the fibre a short distance (say 1 or 2 mm) from the detector thus illuminating a larger area of the detector and "integrating" out the variation of responsivity across the surface of the device. This was not attempted since one of the detectors had a connection to one of its leads which might have been damaged in the process. Filling the gap between the fibre and detector with index matching fluid would help reduce scattering and reflection from scratches and slightly curved surfaces. This method would work best with a large detector which would make positioning less critical.

The other method of improving the fibre-detector coupling would be to cement to the detector a fibre with a larger core and higher NA than any sample fibre. This large fibre would capture all of the light from the sample and would reduce the difficulty of positioning the "sample fibre". Since the fibre "pigtail" would only have to be positioned on the detector once, the extra effort required to position it on a small detector would be negligible compared to the noise reduction possible (smaller detectors are discussed later in this section).

Either positioning the fibre away from the detector or attaching a large core pigtail to the detector should reduce the error in the fibre-detector joint to much less than ±1%, that being the error in a fibre to fibre butt joint between equal size fibres. However, there is still the pickup fibre to sample fibre butt joint. A differential screw positioner would help in making the joint but probably would not reduce the error substantially.

The measurement error should be reduced to between ±1% and ± 1.4% by the changes described above, greater accuracy would apparently require another technique.

Signal Improvements

For the BNR 319 fibre the signal cannot be appreciably increased by using a lower f/# monochromator. This is because image of the output slit formed by the output adaptor lens is much larger than the fibre core and has a low enough f/# to fill the fibre NA. The only improvement which a lower f/# monochromator would allow is to reduce the effects of lens aberration on the brightness of the image since the slit would require less demagnification to fill the fibre NA. For fibre with a large core (≃110 μm) or large NA (≃.25) a lower f/# monochromator would be required or a definate loss in signal would result.

A brighter source (i.e. one which has a larger output in terms of Watts Steradians^{-1}m^{-2}) would also increase the signal but the author knows of no practical sources with a higher brightness as well as a suitable area and emission spectrum.

Thus the only improvement in signal level would come from reducing the effects of lens aberration by using a lower f/# monochromator which requires less demagnification from the output adaptor lens. This would result in a larger image (by design) and would also facilitate placing both pickup fibres in a position to pick up the maximum amount of light.

Noise Reductions

The noise level is primarily determined by the detectors. Cooling the existing detectors to -78°C would increase the SNR by a factor of 3 (by reducing the detector noise).[8] Cooling the existing detectors to -196°C (liquid nitrogen) would increase the SNR by a factor of 10 over room temperature operation[8] (assuming the preamp was upgraded to reduce its noise output). Since the noise generated by a detector is generally proportional to the square root of the detector's area[8], reducing the detector size to 1 mm square from 2 mm square would double the SNR (at any detector temperature). Even smaller detectors could be used without a loss of signal since the fibres are typically less than 0.2 mm diameter, particularly if a large core fibre pigtail was permanently attached to the detector to allow more repeatable fibre-detector coupling. A 0.25 mm square detector would give eight times the SNR of the 2 mm detector.

Germanium photodiodes could be used in place of the PbS detectors. Ge detectors of the same area and at the same temperature would give 30% higher SNR at .9 μm, twice the SNR at 1.5 μm, the same SNR at 1.6 μm but have very poor performance past 1.7 μm.[9] The Ge diodes are well matched to the spectral range of the system and would result in a 3 dB SNR improvement near 1.5 μm. Cooling the Ge diodes results in the same performance increase as it does for PbS at -78°C, but manufacturers differ on whether cooling to -196°C will increase the performance to 10 times that of room temperature(9,10). The noise output of a Ge diode can also be expected to be proportional to the square root of the area. Cementing a pigtail to a Ge diode is particularly attractive since many photodiodes have a fine bond wire which arches from the header to the diode and which could easily be broken by a fibre.

The noise which passes through the processing electronics could be reduced by reducing the bandwidth of the preamp, however, with a 20% duty cycle pulse this would result in little gain in SNR as harmonics of 100 Hz make up a large part of the signal. If the signal was changed to a 50% duty cycle pulse it could be filtered down to a sinewave at 100 Hz (the chopper frequency) with no loss in amplitude (although the zero to peak value of the signal would be approximately 60% that of the 20% duty cycle pulse). This is because the harmonics contain a smaller percentage of the signal power. The noise which would be filtered out by this process and which would otherwise pass through the processing electronics, is the noise at integer multiples of 100 Hz from 200 Hz to 1.2 KHz inclusive. This should reduce the noise by a factor of approximately 3 depending on the noise spectral density, however, only an improvement of about two times could be expected in the SNR (due to the reduction of the zero to peak amplitude).

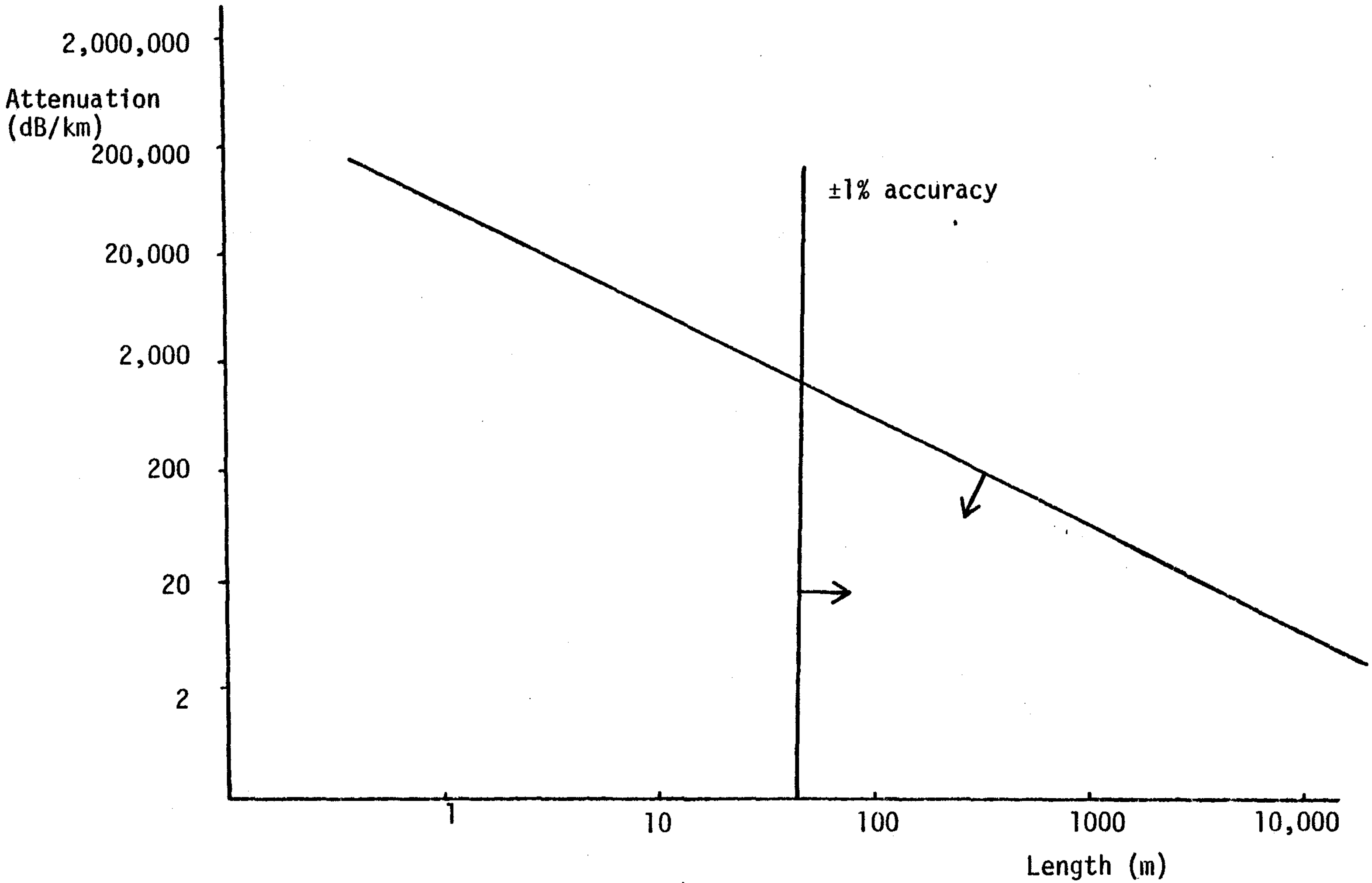
As a reasonable example of the benefits to be gained from some of the changes described above, figure 3-3 has been replotted assuming a 0.25 mm square PbS detector cooled to -78°C. The result, shown in figure 4-1, is a gain of 13.8 dB in allowable loss.

Comparison of Fibre Testing Methods

If the measurement error was reduced to ±1% then the minimum sample length, using the replacement method, would be reduced to 44 m. This is also shown in figure 4-1. While more extensive changes would increase the allowable attenuation, the minimum sample length cannot apparently be reduced below approximately 40 m (i.e. approximately 1% measurement error) using the replacement method and the present fibre coupling techniques.

The "on-line" method requires that the sample fibre be damaged (slowly) while connected to the transmission measuring system. The spectral attenuation of the sample is scanned repeatedly as it is damaged. Since the sample coupling is not disturbed it has no effect on the measurement. However, this method is not practical for long term (weeks say) studies of annealing as the sample must remain connected to the system until the study is over.

Without the error due to the sample coupling repeatability the measurement error is caused by drift and residual errors left after correcting the divider non-linearity. Properly done the corrections should leave a residual division error considerably less than the ±0.25% peak drift (see Chapter 3). Assuming then that the measurement error is given by the peak drift of ±0.25% the



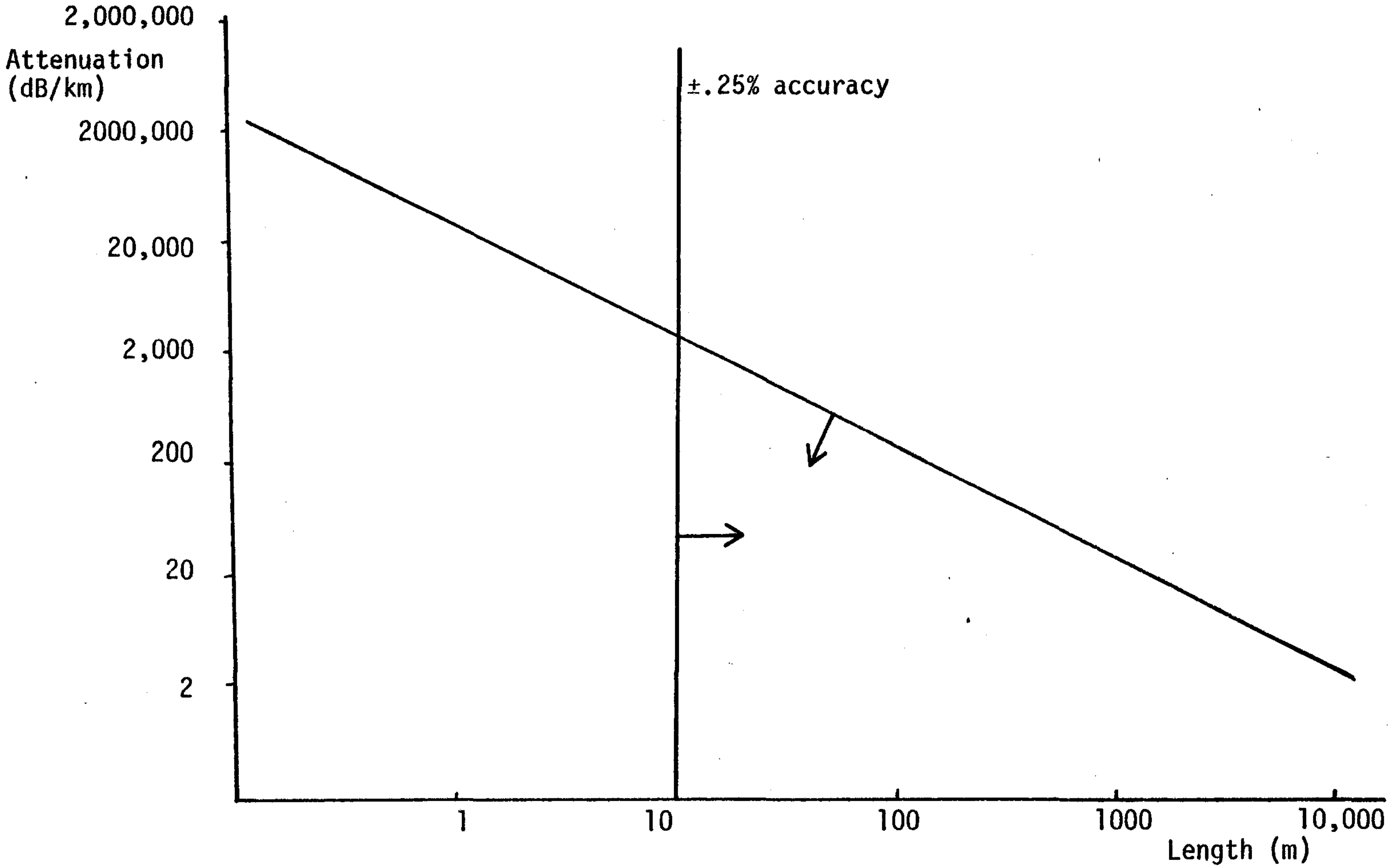
Measurement Boundaries Improvement due to Lower Noise and Improved Coupling

Figure 4-1

minimum sample length is 10 m. This is shown in figure 4-2 along with the attenuation limit line set by the existing detector. Attenuations up to 2000 dB/km can be measured with 10 m samples using this method and the existing detector.

Summary

The system, as constructed, has a measurement accuracy of 1.4% (assuming the sample fibre is butted to another fibre at both ends) and a maximum sample loss of 20 dB (.33 second time constant). This requires a 60 m sample to achieve ±1 dB/km accuracy. The maximum sample attenuation is 330 dB/km. Reasonable improvements to the detector and detector coupling would reduce the minimum sample length to 45 m and increase the attenuation to 750 dB/km. The use of the in-line method instead of the replacement method reduced the minimum sample length to 10 m. The maximum attenuation, using the in-line method, is 2000 dB/km using the existing detector or 3400 dB/km with the smaller detector.



Measurement Boundaries Improvement Due to the In-line Method

Figure 4-2

APPENDIX A

The procedure for operating the transmission measuring system is given in this appendix. The operating procedure assumes that the system is properly adjusted and aligned. All controls necessary for the operation of the electronics are on the front and back panels of the electronics box. The layout of the controls is given in figures A-1 and A-2.

The alignment procedure and the location of the important components on each circuit board are given in Appendix B. Typical operating waveforms and voltages are also found in Appendix B.

The following equipment, which is not physically part of the system, is required:

- microscope, preferably stereo, to examine fibre ends and to aid in positioning fibres (80 power is adequate)
- a voltmeter to measure the reference level
- an oscilloscope to monitor the sample and reference signals from the preamp and to set the chopper frequency.

In addition to connecting the above equipment the connection of the following items to the electronics box should be verified:

- the lowpass filter should be connected to the ±15V outputs, the transmittance output and the chart recorder input.
- the chopper monitor should be connected to +5 V and its

Figure A-1

Front Panel Layout

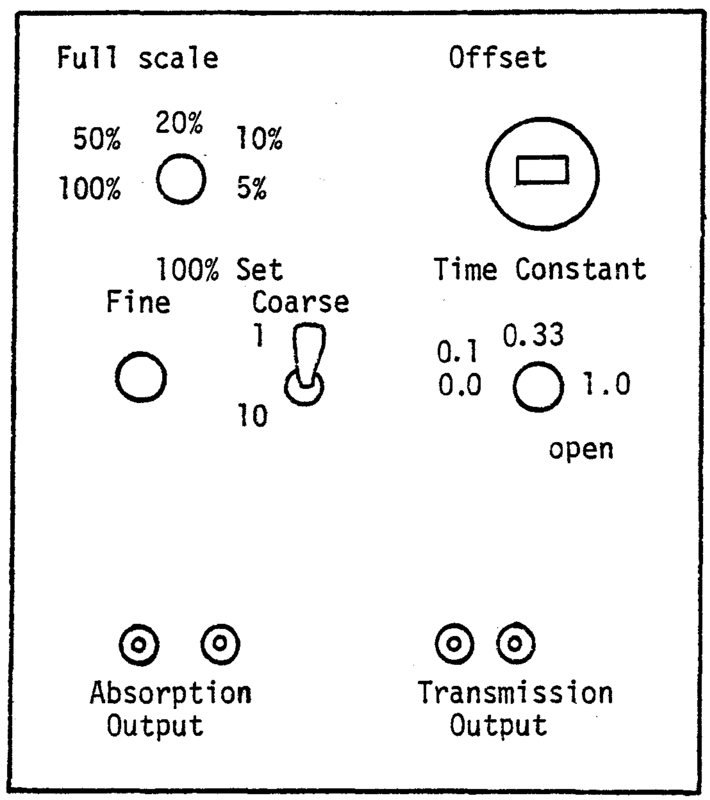
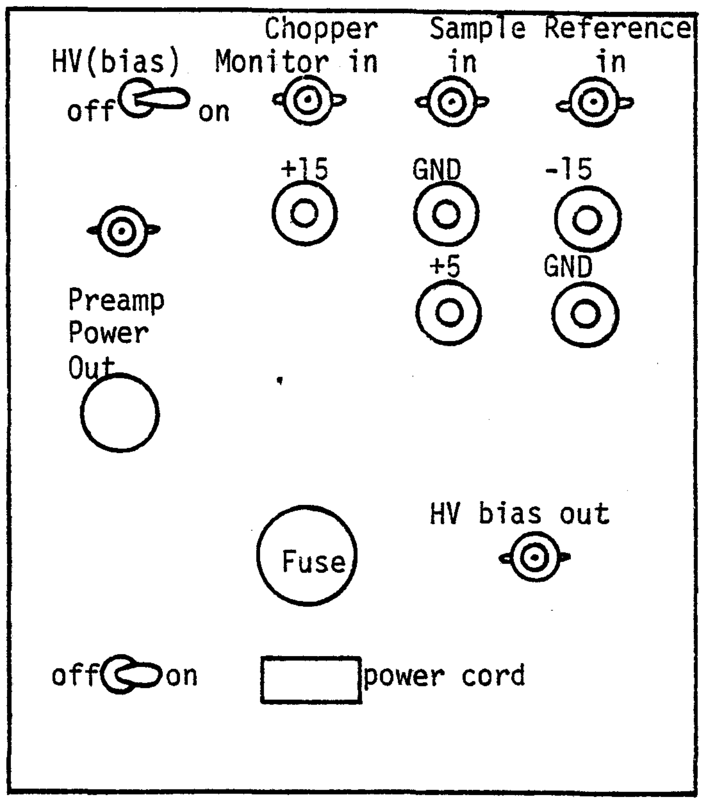


Figure A-2

Rear Panel Layout



output should be connected to the chopper monitor jack.

- the preamp cables (power, detector bias, reference and sample).

The operation of the system can be broken down into the following major steps:

1. set the required parameters on the electronics box and monochromator
2. turn on the electronics power (only turn on the detector bias if the fibres are installed at the detector end and the preamp box cover is closed)
3. install the fibre to be tested (roughly align all butt joints)
4. turn on the lamp, chopper, the detector bias voltage (if not already on) and "fine tune" the fibre coupling
5. start the chart recorder and scan the monochromator through the desired wavelength range.

These steps are ordered to suit the warm-up requirement of the electronics and to minimize the use of the chopper and lamp. The chopper motor and lamp both have limited lifetimes and should be turned off when not required. The detector bias should never be turned on when the preamp box cover is open, since the signal resulting from the room lighting could damage the preamp.

These five steps are discussed in detail below for the case where the first of a set of fibres is to be tested. Discussion of the steps required to install and test any other fibre of the set follows the more general method for testing the first fibre. It is assumed that the reference pickup fibre is connected to the reference detector and that all samples will be compared to the reference pickup.

The first step is to set the required parameters on the electronics box and monochromator. The parameters are listed below (only typical values can be given as different applications require different settings).

- set the time constant (typically 0.1 sec)
- set scale switch to 100%
- set offset to 000
- set 100% set switch to X1
- set the slit opening (typically 400 μm)
- set the starting wavelength (typically .9 μm which corresponds to 4500 Å on the monochromator scale)
- set the scanning speed (typically 500 Å/min on the monochromator selector for 0.1 sec time constant)
- set the chart recorder speed (typically one inch/min)

The second step is to turn on the power for the electronics. The steps required are:

- turn off the high voltage (detector bias) switch
- turn on monitoring instruments such as the voltmeter and the oscilloscope
- turn on the chart recorder
- turn on the main power switch on the electronics box.

The third step is to install the standard (undamaged) sample fibre. The procedure used depends on the coupling method selected for each end of the sample fibre. In general the following steps apply:

- expose at least 5 cm of the fibre at each end of the sample for mode stripping (if not already done)
- cleave or clean both ends (as required)
- fasten one sample fibre end to the jig holding the sample pickup fibre
- fasten the other end of the sample fibre in front of the detector or to the jig holding the detector pigtail
- mode strip both ends of the sample fibre and the detector end of the reference pickup fibre
- roughly align the fibres in any fibre to fibre butt joints and ensure that the sample is properly held on the detector (if applicable)
- replace the preamp box cover.

The fourth step is to turn on the chopper, lamp and detector bias voltage. After these steps the fibre to fibre butt joints are "fine tuned". This is done by moving the fibres laterally to peak the value of the sample signal (measured on the digital voltmeter). The fibre to fibre gap is adjusted when the fibres are almost laterally aligned. In the finished joint only a very thin (much less than a core diameter) layer of index matching oil should be left between the fibre ends. The 100% set controls can be used to maintain the sample level at a reasonable value (say between 8 and 10V).

The fifth step requires scanning through the wavelength range to determine where the system output (the ratio of the sample level to the reference level) is at a maximum and setting the maximum output to 10V using the 100% set controls (full scale on the chart recorder must be 10V for maximum resolution). The system is then scanned through the desired wavelength range and the output is recorded. The output obtained from the scan of the standard fibre is called the "calibration curve". The system output for any other sample in the set can be converted to an absolute transmission by dividing by the calibration curve. The calibration curve must be corrected for divider nonlinearity before it is used to find the transmission. This correction requires a plot of the reference signal level versus wavelength which can be recorded manually while scanning the standard sample. Once the reference signal level and calibration curve have been measured the following parameters must not be changed until all samples in the set have been tested:

- the 100% Set control setting
- the slit width
- the position of any of the optical components or the pickup fibres (in the output adaptor)

- the lamp voltage (when on)
- the reference pickup fibre-detector butt joint.

The zero level is set during the alignment procedure (see Appendix B) of the offset and scale adjust circuit and never been seen to change. Because of nonlinearities in the divider the divider output does not in general go to zero for zero signal input. Zero signal can, if desired, be checked at the output from the offset and scale adjust circuit.

The procedure for testing the rest of a set of fibres is considerably simpler than that for the first (standard) fibre. Only the following steps are required:

- turn off the HV bias and allow at least 10 seconds for charge to drain from the filter capacitors before opening the preamp box
- turn off the lamp (noting its operating voltage) and chopper
- remove the previous sample and roughly position the new sample
- turn on the detector bias (after closing the preamp box cover), lamp and chopper
- "fine tune" the positioning of the sample; adjust the time constant (and therefore scanning speed) and scale factor (note carefully on the chart) if required to obtain an adequate SNR and signal

- scan the new sample

The output from the sample should be corrected for divider nonlinearities and scaled before dividing by the calibration curve to obtain the transmission.

To check that the calibration curve has not been changed during the testing of the samples it must be redone (as the last sample).

APPENDIX B

The procedures for aligning the optics and adjusting the electronics are given in this appendix. The locations of the electronic circuit cards are shown in figure B-1. The locations of the major electronic components, particularly those required for alignment, are shown in figures B-2 through B-8. All circuit boards are shown from the top view.

The alignment is divided into two parts. The alignment of the optics and monochromator is discussed first. It is followed by the alignment procedure for the electronics.

The alignment of the optics in the light source is critical to obtaining both good resolution and the largest possible signal. Of great importance is the alignment of the light source, in particular the lamp and consdensor lens, with the monochromator optics. This is because these components determine the amount of light which leaves the monochromator and its spectral width. The lens in the output adaptor must also be aligned to get the maximum amount of light into the pickup fibres and to fill the NA of the pickup fibres.

The light source is roughly aligned with the monochromator by setting the lens and bulb such that a clear image of the filament of the bulb is formed on the entrance slit of the monochromator. This must of course be done with the filter out of the system as

Figure B-1

Circuit Boards

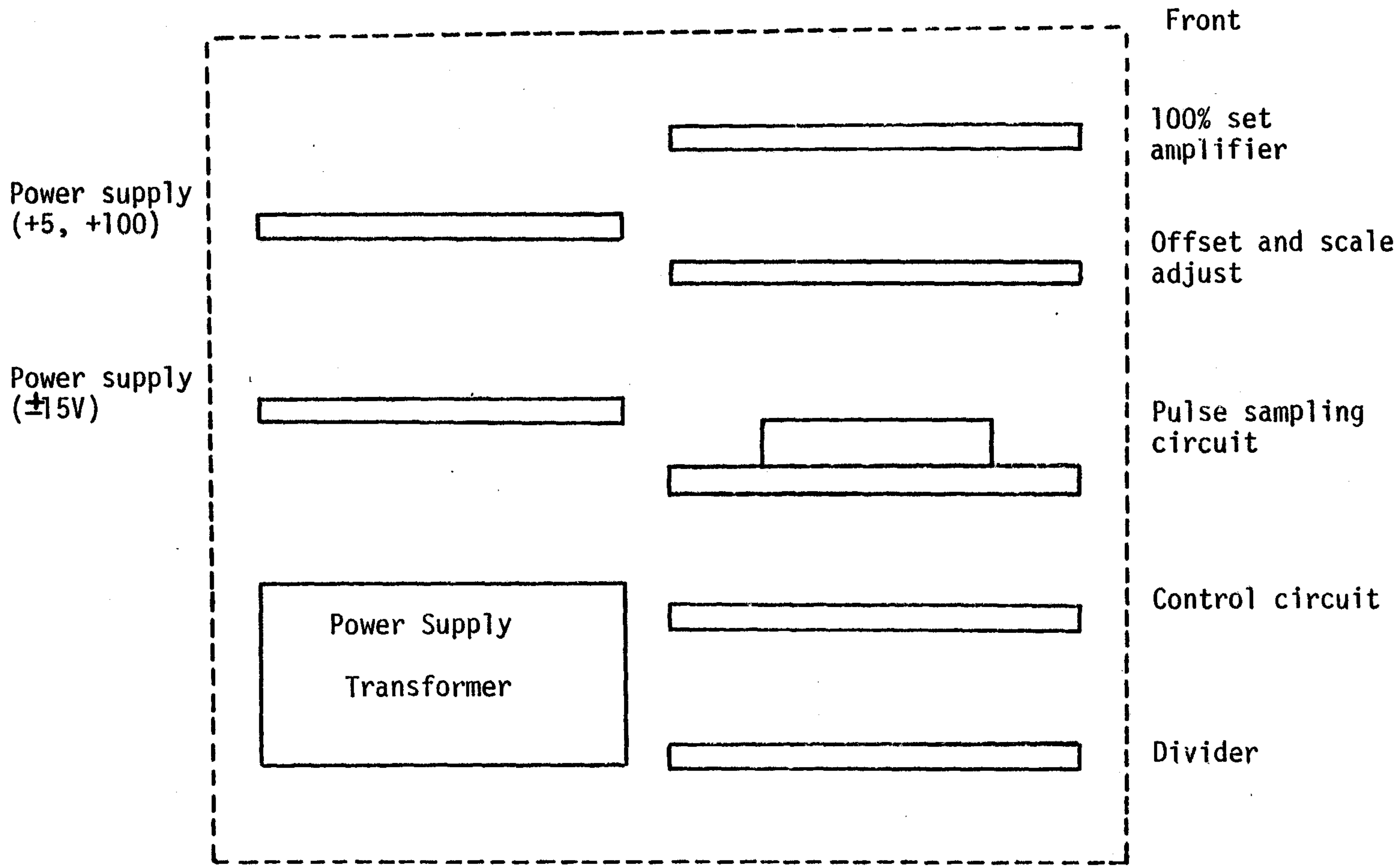


Figure B-2

Preamplifier Layout

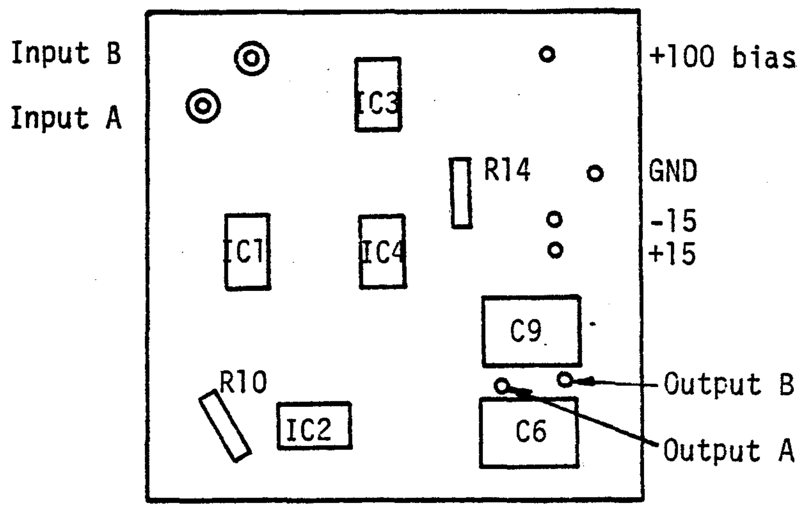


Figure B-3

100% Set Amplifier Layout

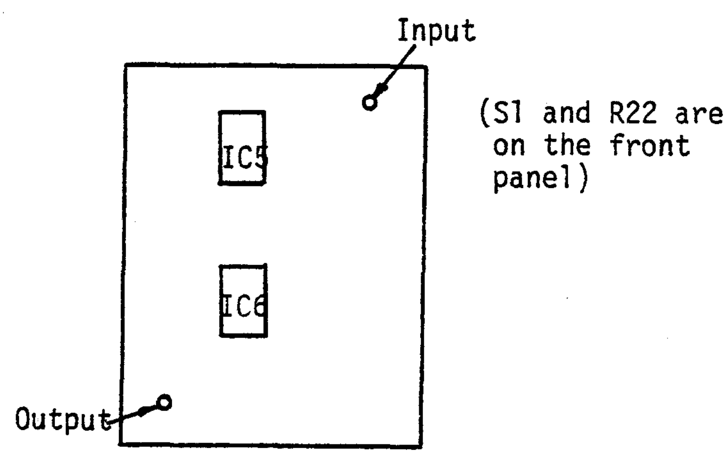
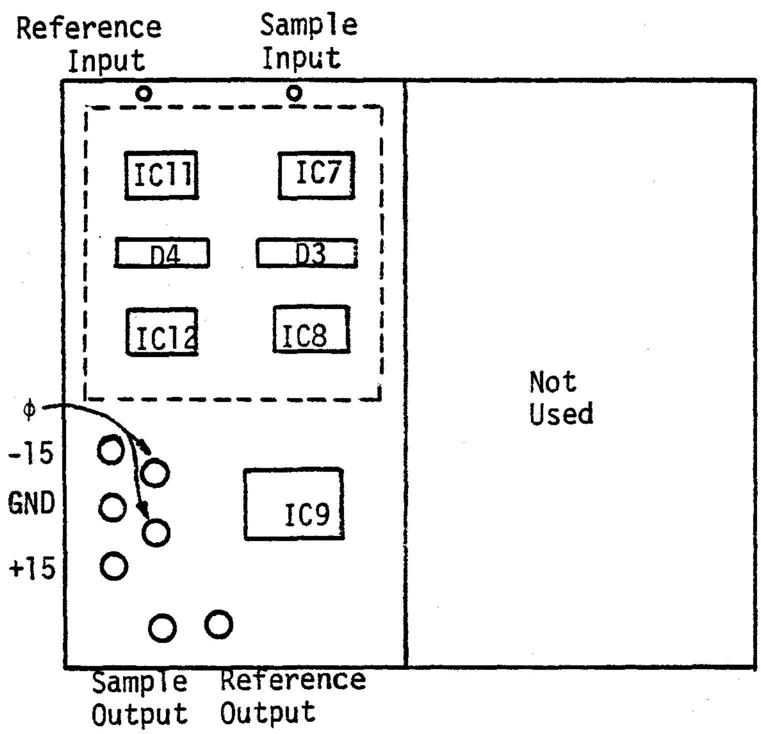
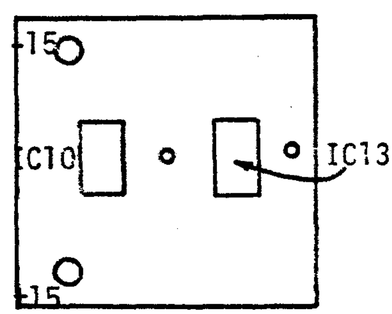


Figure B-4

Pulse Sampling Circuit Layout



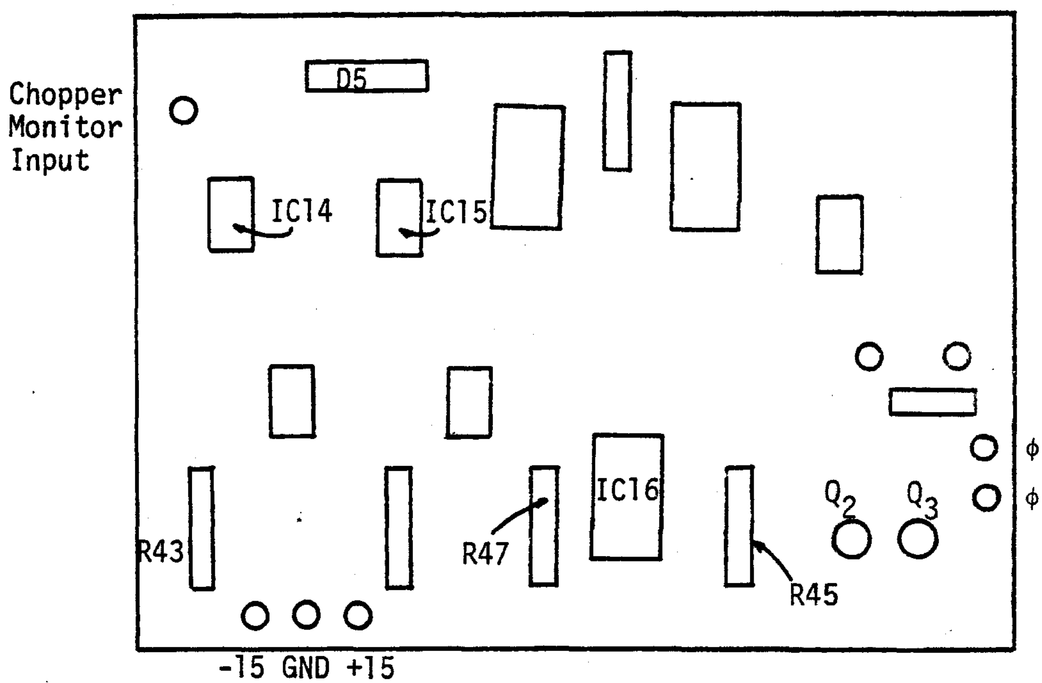


Notes : the small board containing IC10 and IC13 is "piggy-backed" on the larger board in the area denoted by the dotted line.

: resistors R28, R29, R30, R35, R36, R37 are attached to S2 located on the front panel

Figure B-5

Control Circuit Board Layout



Note : unlabelled components are no longer in use

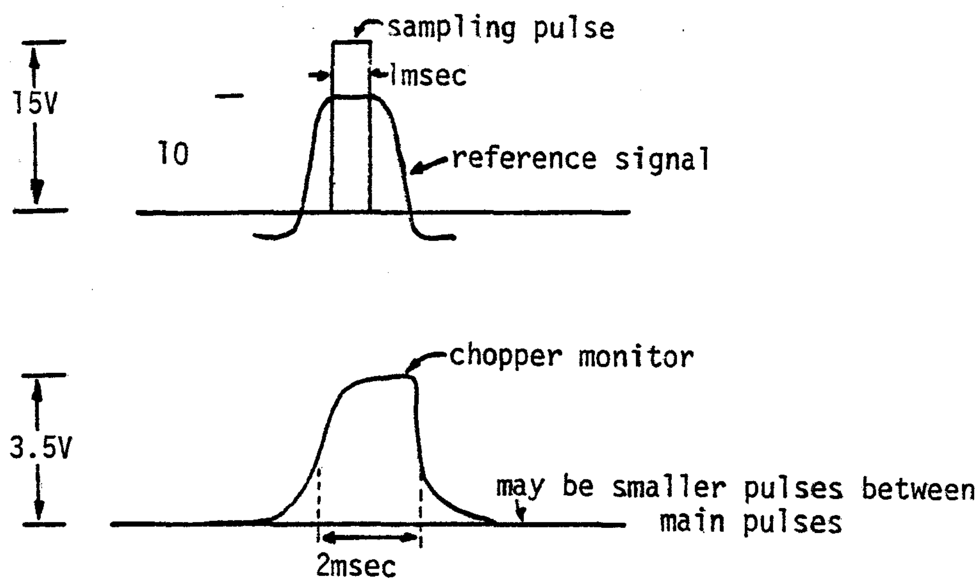
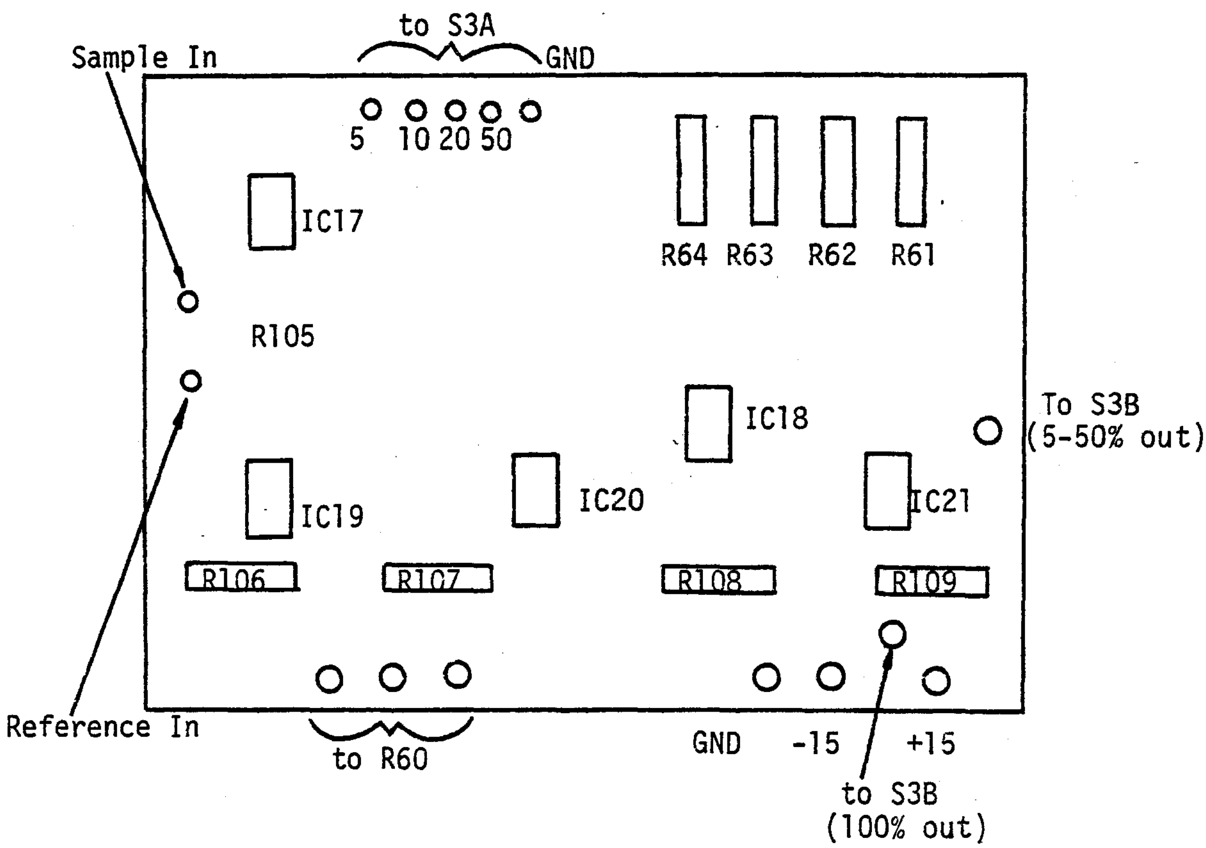


Figure B-6

Offset and Scale Adjust Circuit Board Layout

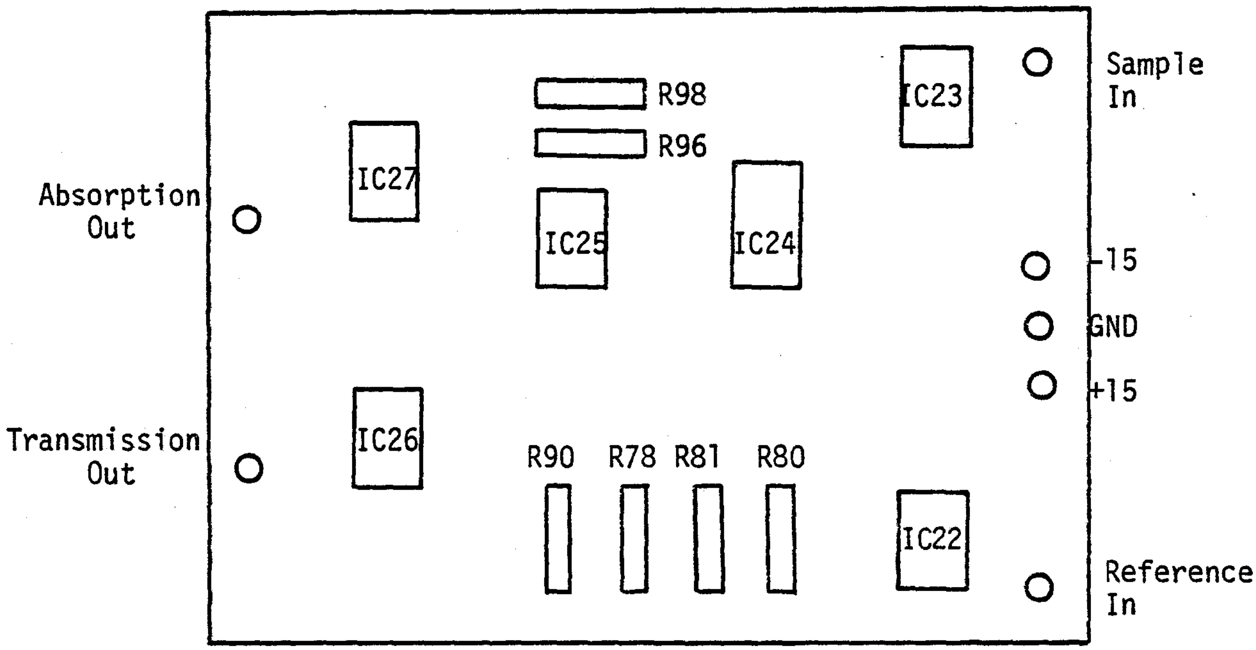


R105 through R109 are offset adjust trimmers for opamps IC17 through IC21

R105	IC17
R106	IC19
R107	IC20
R108	IC18
R109	IC21

Figure B-7

Divider Circuit Layout

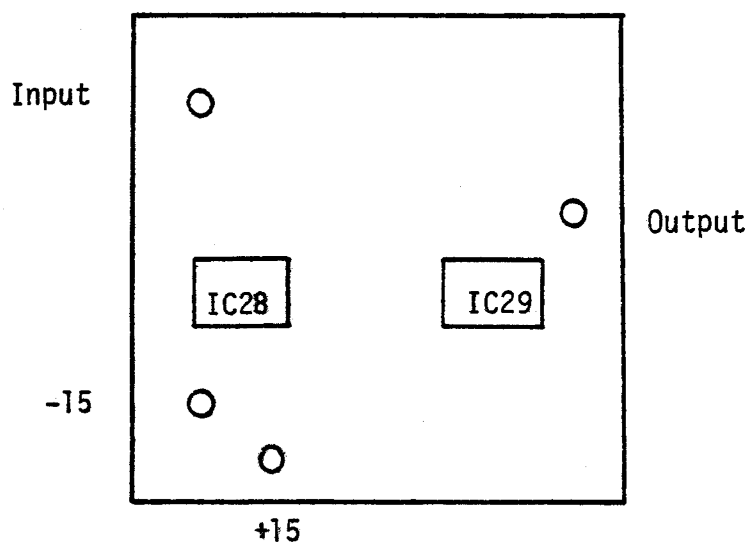


Correspondence Between Motorola Manual Terminology and above Circuit

Divider (above)	Motorola (Ref. 6)
Sample in	Vz
Reference in	Vx
Transmission output	Vy
R78	Scale factor
R80	y offset adjust
R81	x offset adjust
R90	Output offset adjust

Figure B-8

Lowpass Filter Circuit Layout



the filter passes virtually no visible light. The lens is moved perpendicular to the optical axis to centre the image and the lamp is moved along the axis to focus the image. When the visible image is in focus on the slit, the infrared image is not due to chromatic aberration in the lens. The infrared image will occur inside the slit since the focal length is longer for longer wavelengths. In addition the filter, when replaced, will cause the infrared image to move approximately 2 mm father inside the slit (assuming the glass in the filter is 6 mm thick and of index 1.5).

To finish the focussing of the light source, the infrared light must be focussed on the input slits. This is done by maximizing the light collected by the pickup fibres, since it cannot be done visually. To do this the filter must be inserted and the monochromator wavelength set to mid-scale (typically 1.2 μm). With the light source roughly aligned, the output adaptor is set up to provide the correct f/# cone of light by setting the correct image and object distances (see Chapter 2). The signal from one of the pickup fibres is peaked by adjusting the three axes of its positioner. The signal is then maximized by moving the lamp. (Moving the lamp away from the condensor should increase the signal.) The sequence of peaking the signal by using the pickup fibre positioner and moving the lamp must be repeated several times to find the "best" signal.

When the "best" signal has been found, the filter should be removed and the location of the visible image determined. The visible image should be within approximately 10 mm of the slit.

The grating should also be uniformly illuminated. If these conditions are not met the process of focussing the light source should be repeated starting with the rough adjustment.

The output adaptor f/# should be checked to ensure that it is at least as small as that required to fill the NA of the fibre. If not the f/# must be reduced and the fine adjustment of the light source focussing should be repeated.

The alignment of the light source and output adaptor is an iterative procedure which is based on the fact that the maximum light will pass through the monochromator when the lamp is focussed on the input slits. It is therefore important that the fine focussing sequence be done several times and the (visual) image position checked to ensure that it is not moving excessively far from the entrance slit.

The alignment of the electronics requires that four circuits be adjusted. These are the preamp, the control circuit, the divider and the offset and full scale circuit.

The preamp has only one adjustment, the gain of the second stage (in each channel). As this change requires replacing two resistors it should only be done once the peak signal has been determined. The preamp gain must be set so that the maximum signal in the reference channel is approximately 12.5V (peak to peak) at the preamp output. This will result in a 10V level at the output of the sample and hold circuit which is the maximum normal input to the divider. The reference signal should be measured with the reference fibres, light source and monochromator set up as they will be for the real test. The gain of IC2 and IC4 are changed by replacing R10 and R14 respectively. Normally, the gain of IC2 and IC4 will be the same. The gain of IC2, G, is given by:

$$G = R12/R' \tag{B-1}$$

where $$R' = R10 \cdot R11/(R10 + R11) \tag{B-2}$$

The required values of R10 (and therefore R14) can easily be obtained from (B-1) and (B-2). The value of R10 for BNR 319 fibre was 1 megohm. This will only have to be changed for a different fibre type.

The control circuit must be adjusted so that the sampling pulses are centered on the reference signal pulses. The sampling pulse should be approximately 1 msec wide. To adjust the control circuit a dual channel oscilloscope should be used to display the reference output of the preamp and the sampling pulse (accessable on the control circuit board). All adjustments are made on the control circuit board.

The width of the sampling pulse is set to 1 msec by adjusting R47. The position of the pulse is set by R43 and R45. R43 should be adjusted so that the sampling pulse occurs at the same place on each signal pulse. Then R43 is used to center the sampling pulse on the signal pulse as shown in figure B-5. When the sampling pulse is stable and centered on the reference signal the control circuit is properly adjusted. Improper adjustment will greatly reduce the SNR.

The offset and full scale circuit must be adjusted to set the gain of the scaling circuit and to null out the offsets of the op amps (the signals are now at zero frequency). These adjustments do not require the lamp or chopper to be on.

To null out the offsets of the op amps the sample and reference inputs should be "disconnected" by setting the time constant switch to its fifth (clockwise) position. The sample and reference inputs of the offset and full scale adjust are then shorted to ground. The offset potentimeter (front panel) is set to zero. The output of each op amp is set as close as possible to zero by adjusting its trimmer. A list of trimmers and op amps is given in figure B6. The op amps must be adjusted in the order in which they are listed. A terminal is connected to the output (pin 6)of each op amp.

The gain of the scale circuit is adjusted next. To do this the signal channel is disconnected from ground and connected to a .500V source. This voltage must be measured using a digital voltmeter. The voltmeter is then connected to the signal input of the divider board. The correct readings for each setting of the "Scale" switch (front panel) are listed below. If these readings are not obtained the corresponding trimmer (also listed below) must be adjusted.

Scale	Reading	Trimmer
100%	.500	
50%	1.000	R64
20%	2.500	R63
10%	5.000	R62
5%	10.000	R61

The reading on the 100% scale cannot be adjusted, if it is not within a few millivolts of .500V then either the input voltage is incorrect, the equipment is set up incorrectly or some component is malfunctioning.

When the offsets and scale factors are correct the offset and scale adjust circuit is properly adjusted. The sample and reference inputs can be disconnected from the power supply and ground respectively and the time constant returned to its former value.

The adjustment of the divider circuit should only be attempted once the description of the circuit has been read (see reference 7). The adjustment procedure for the divider is also given in reference 7. The correspondence between the terminology of reference 7 and that of this report is given in figure B-7. The divider should be adjusted to give the minimum error for inputs in the 5 to 10V range (as shown in figure 3-2).

The adjustment of the absorption output is not covered in reference 7. To adjust it, first adjust R98 until the voltage on R98's wiper is 5.000V. Then adjust R96 so that the absorption is ten volts minus the transmission (the transmission output should be between 0 and 10V). This completes the adjustment of the electronics. Typical voltages are listed below for reference.

Item	Norminal Value	Measured Value
Power supply	+15	15 ± .5
Power supply	-15	-15 ± .5
Power supply	+5	5 ± .5

Typical signal shapes and amplitudes are given in figure B-5.

The single remaining item to be adjusted is the positioning of the fibre holders in front of the detectors. As discussed in Chapter 2 the spectral responsivity of the detectors appears to vary across the surface. Thus the fibre holders must be adjusted until the fibres illuminate areas of similar spectral responsivity. The adjustment is done by loosening the two screws holding one of the apertures (BNR "half-splices") which position the fibres and moving it to new position. The screws are retightened and the preamp box closed. Positioning of the aperture is done by trial and error. The slope of the reference line indicates how closely matched the two detector areas are. It should be possible to reduce the slope of the reference line to several percent. The reference line slope is discussed in more detail in Chapter 2.

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