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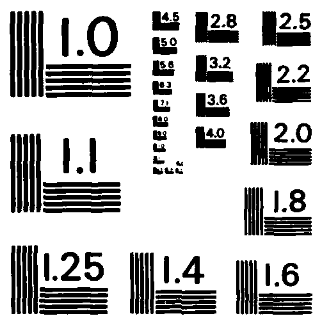

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WEAPONS SYSTEMS RESEARCH LABORATORY

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TECHNICAL MEMORANDUM
WSRL-0342-TM

LARGE DIAMETER OPTICAL SLIP-RINGS

P.J. BUTTERY

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TECHNICAL MEMORANDUM

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LARGE DIAMETER OPTICAL SLIP-RINGS

P.J. Buttery

S U M M A R Y

This technical memorandum describes two different types of optical slip-rings developed for use with a rotating platform which has a column diameter of 123 mm. The preferred type is then combined with an "on-axis" coupling (described elsewhere) for use on an experimental track-while-scan secondary radar system.

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1. INTRODUCTION

The transfer of data to and from equipment mounted on a rotating platform such as is used for the aerial mounting of a track-while-scan radar system involves some sort of rotating coupling. Mechanical slip-rings are available which can be used to transfer electrical power and/or electrical signals at quite high frequency but their main drawbacks from the point of view of signals are the noise introduced at the brushes and crosstalk between adjacent channels. Even when these can be reduced to acceptable levels, performance deteriorates with running time and in this case there is a virtually continuously rotating aerial system.

What is required is a frictionless method of coupling which will not degrade with time. With the rise of fibre-optic technology and the availability of suitable opto-electronic components, it was decided to develop a rotating optical coupling which, while general purpose in nature, would meet the requirements of the experimental radar system. It would also make use of the inherent advantages of an optical system of electrical isolation which eliminates many grounding and safety related problems, EMI and RFI immunity and additionally, it is neither susceptible to nor does it emit electromagnetic radiation.

This paper describes two different types of optical slip-rings developed during 1981 to 82 as part of the Guided Weapon Technology Task DST 78/057 and also the combined version that was finally used.

2. INITIAL DESIGN REQUIREMENTS

The aerial platform is mounted on a column or tube and rotates at a speed of approximately one revolution in two seconds. The most suitable place to have the optical coupling would be on the column axis allowing a simple system of lenses or similar at the bottom of the column to couple the light from the fixed to the moving part. Unfortunately the initial configuration of the experimental tracking mount necesssitated two waveguides inside the column and a rotating waveguide joint at the bottom. The alternative was to mount the optical coupling on the outside of the column in a manner analogous to mechanical slip-rings. The diameter of the column at this point was in the order of 120 mm.

The data to be transferred from the equipment on the tracking mount could be in various formats but it was decided that a typical channel was an eight bit digital word plus parity bits in two microseconds. This gave the requirement as 5 Mbit/s with the possibility that the data may consist of all ones or all zeros.

Initially two different designs were investigated and experimental models were built to establish the practicality of each. The first type consisted of two rings of optical fibres lying parallel to the axis of the column and "face to face". One ring being attached to the rotating platform and the other to the fixed mounting. From the back of each ring the fibres were collected into bundles and led to either a transmitting LED (light emitting diode) or a photodiode receiver which could be located some distance away from the coupling.

The second type consisted of one or more transmitting LEDs mounted on the rotating column and facing radially outwards and a ring of photodiodes opposite the LEDs facing radially inwards and connected in parallel. Light from the LEDs would thus scan round the ring of photodiodes illuminating at least one at any time in sequence.

3. EXPERIMENTAL SLIP-RINGS

To investigate the two basically different types of slip-rings that were being considered scale models were built and used in experiments to establish their suitability for use in the full scale version. Since it was highly probable that a two way flow of data would eventually be required, consideration had to be given to whether the channel could be bidirectional or whether two separate channels would have to be used. It was also planned that as far as possible the electronic circuits of the transmitter and receiver would be the same for each type of slip-ring. Development of these is discussed separately.

3.1 Ring of diodes

A half scale model was used initially. It consisted of a fixed ring of photodiodes at right angles to the vertical column axis and facing inwards and a LED projecting through the wall of the rotating column at the same level. The photodiodes were connected in parallel so that the signal detected by one or more of them would be amplified in the receiver and provide a composite output. The prime requirements for both the LED and the photodiodes were fast speed of response and a rise time in the order of 10 ns and a wide angle of operation. This led to the selection of silicon PIN photodiodes as detectors which had the following properties:

broad spectral response covering visual and near infrared,

high speed of response with less than 1 ns rise and fall times,

wide viewing angle of 90°

high sensitivity

low capacitance,

low noise.

To operate near the peak of the silicon photodiode response curve the LED which is a narrow band device has to be a red or infrared (IRED) emitter. The gallium arsenide IRED chosen had the following properties:

emission peaking at 900 nm (near infrared)

emission rise and fall times of 10 ns

wide radiation polar diagram

high radiant output.

Both types of diode are available in a hermetic metal package for stability and high reliability with a long life of greater than one thousand hours.

Initial consideration of the physical relationship between a typical IRED and a typical photodiode is given in figure 1.

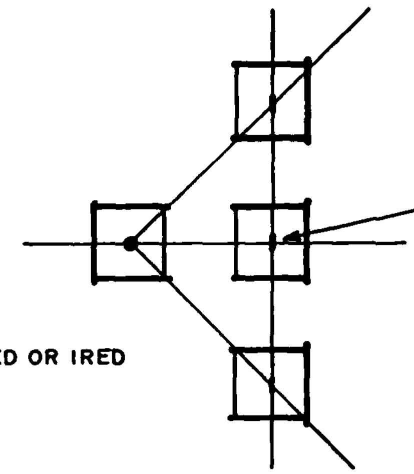


Figure 1. Simplified LED to photodiode relationship

The important characteristics of suitable diodes are:

<u>FPE 510 (emitter) at 100 mA</u>			<u>HP 5082-4220 (detector)</u>		
IR output power		0.5 mW	sensitive area		0.2 mm^2
axial intensity		1.0 mW/sr	flux responsivity		0.5 μA/μW
relative intensity	0°	1.0	directional sensitivity	0°	1.0
	30°	0.5		30°	0.9
	45°	0.1		45°	0.6

For a spherical distribution of light,

$$\text{total radiant incidence } H_T = \frac{\text{Power output}}{4\pi\ (\text{distance})^2}$$

with a 90° cone of radiance and a distance of separation of 1 cm

$$H = \frac{0.5}{\pi(1)^2} = 160\ \mu W/cm^2$$

power received by the sensitive area = 160 x 0.002 = 0.32 μW
and detector output = 0.32 x 0.5 = 0.16 μA

This would be the ideal radiation pattern as a relative movement between the diodes on parallel planes would not produce any amplitude modulation. However considering the emitter polar diagram:

for 90° cone of radiation and a distance of 1 cm,

$$\text{radiation on axis} = \frac{1\ \text{mW/sr}}{(1)^2} \times 0.002\ \text{cm}^2 = 2\mu\text{W}$$

$$30^\circ\ \text{off axis} = 2.0 \times 0.5 = 1\ \mu\text{W}$$

$$45^\circ\ \text{off axis} = 2.0 \times 0.1 = 0.2\ \mu\text{W}$$

The polar diagram of this detector has little effect on the power received except at 45° off axis when moving parallel to the emitter. If either diode is moving on a circular path this must be taken into account especially if the radius becomes small. Figure 2 shows this effect using one IRED and two photodiodes with signal amplitude in arbitrary units proportional to total diode current. Note that "d" is the separation between faces in mm, add 6 mm for distance between emitting and detecting surfaces. From the above we can see that for a situation with one IRED emitter and a number of photodiodes with their outputs connected in parallel, the separation between the photodiodes should be not greater than the distance between the emitting and detecting surfaces for amplitude modulation of a reasonable value. The order of the detector output also gives an indication of the amplification required to provide an output signal at normal logic levels.

To give a larger output signal and improve signal/noise ratio, two or three IREDs were used driven in parallel. This has the additional advantage of reducing the amplitude modulation due to rotation. It was found experimentally that the best combination was to use three IREDs with a centre spacing of 4/3 the distance between the photodiode centres. There was also the advantage that reduced operation was still possible in the event of failure of one IRED or one photodiode of a group.

A full sized experimental model was then built to suit a 123 mm diameter shaft. This is shown sectionalised in figure 3. It comprises two slip-rings (made in two halves), one of which is used for an up channel and consists of IREDs mounted on the baseplate and the photodiode ring mounted on the rotating column. The down link has the IREDs rotating and the photodiodes fixed. Thus the aluminium ring fixed to the baseplate carries the three IREDs of the uplink and the ring of photodiodes of the down link. The aluminium ring on the column carries the down link IREDs and the uplink photodiodes. The IREDs were located in holes drilled in each ring but the photodiodes were mounted on a strip of flexible printed circuit card with copper strip on the back side etched to provide parallel connection of the diodes. A photograph of the parts is shown in figure 4 including the experimental transmitter and receiver modules.

No major difficulties were experienced with these slip-rings although much time was spent in reducing electrical interference between the transmitter and the receiver. This was mainly due to radiation from the IRED leads which had to be kept short. A modification was also made to the IRED housing to keep the leads completely shielded by the aluminium block. Similarly, the photodiode ring was decoupled by distributed condensers on the voltage supply line and the lead to the receiver completely shielded as described in more detail in paragraph 4.3.

It can be seen that additional channels can easily be added if required, the only difficulties being encountered by the physical positioning of the transmitter and receiver. The detector part of the receiver in particular must be close to the photodioded ring as described in Section 4.

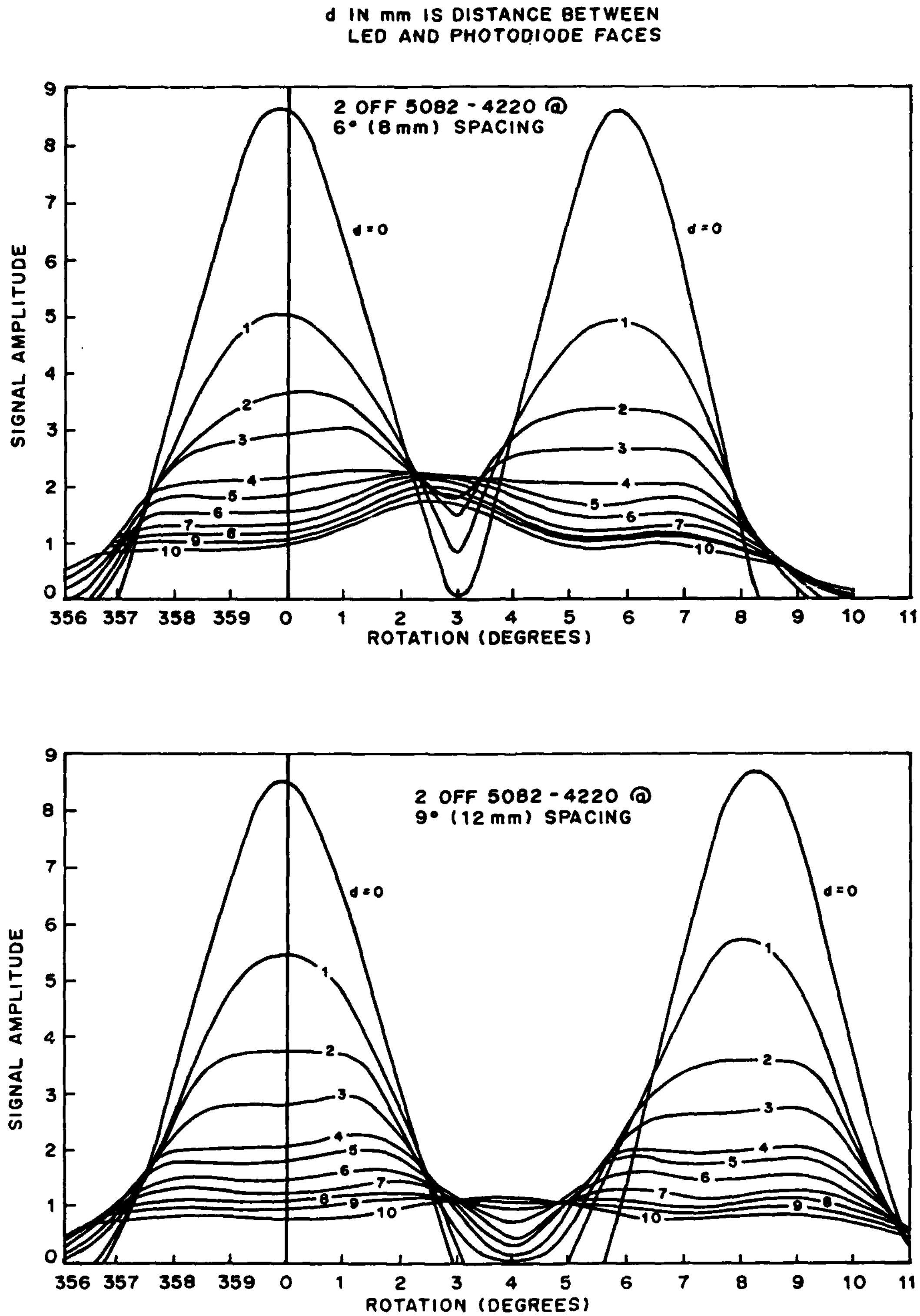


Figure 2. Effect of increasing separation between one IRED and two photodiodes

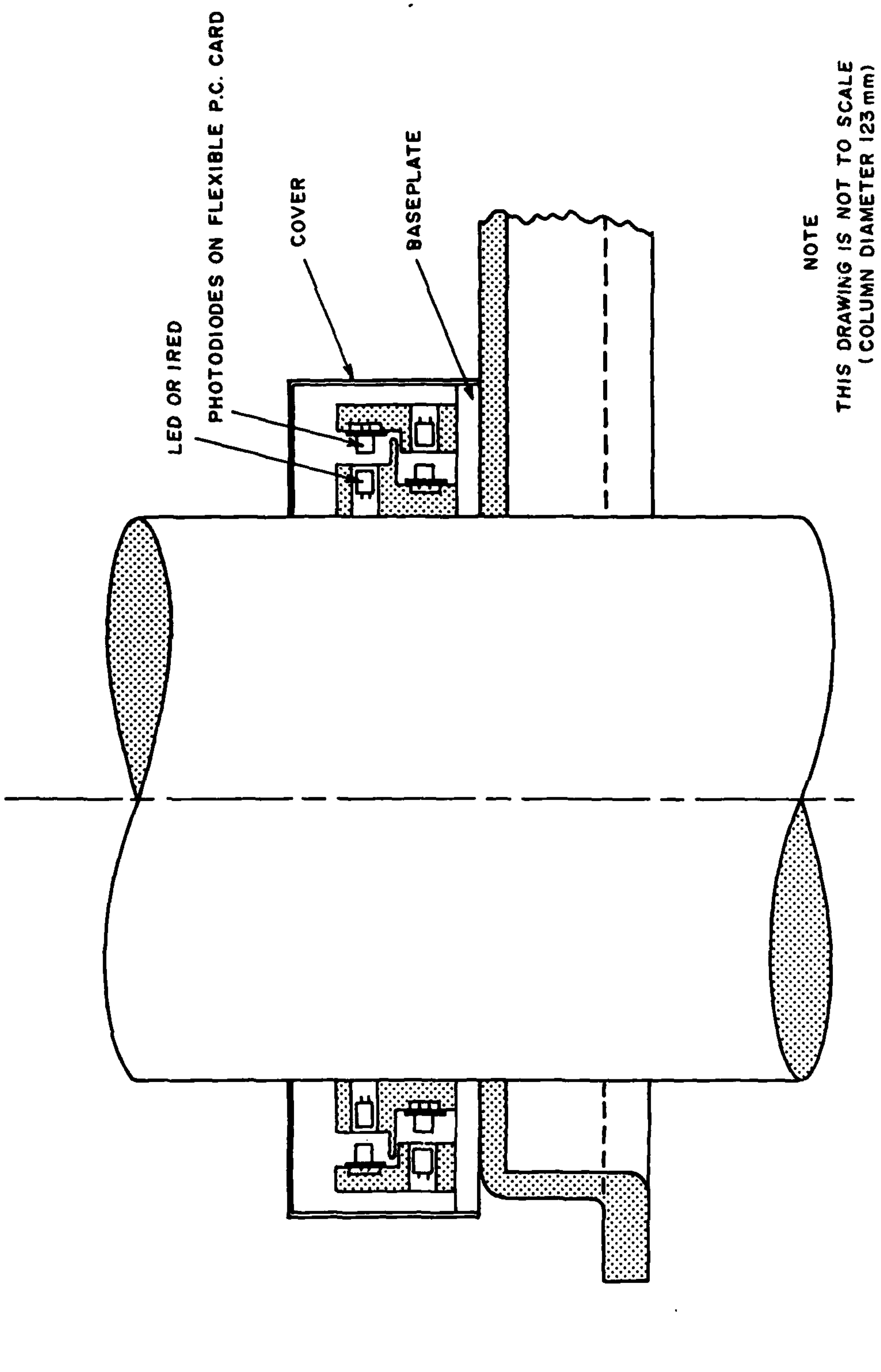


Figure 3. Section through experimental slip-ring assembly

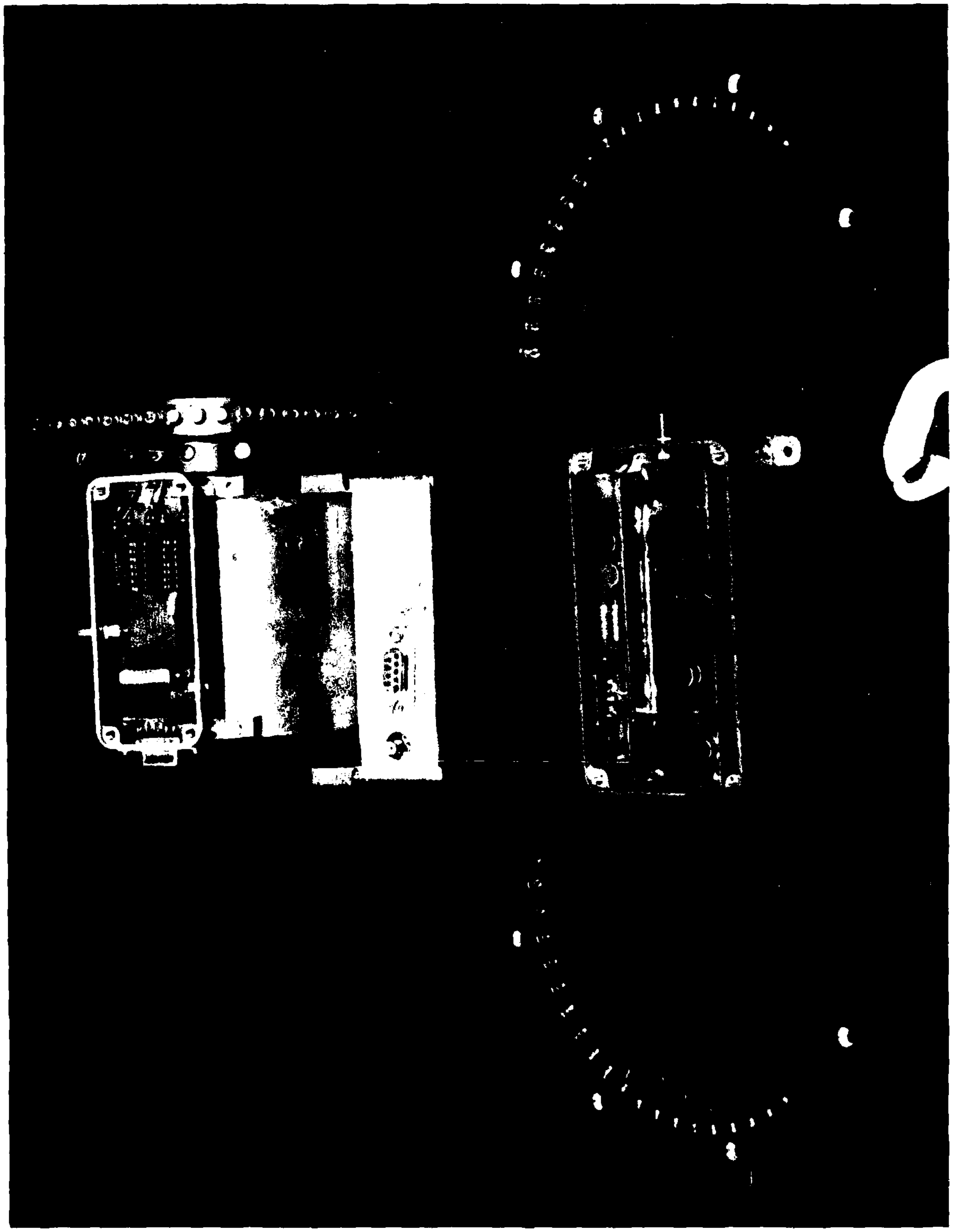


Figure 4. Photograph of experimental slip-ring parts

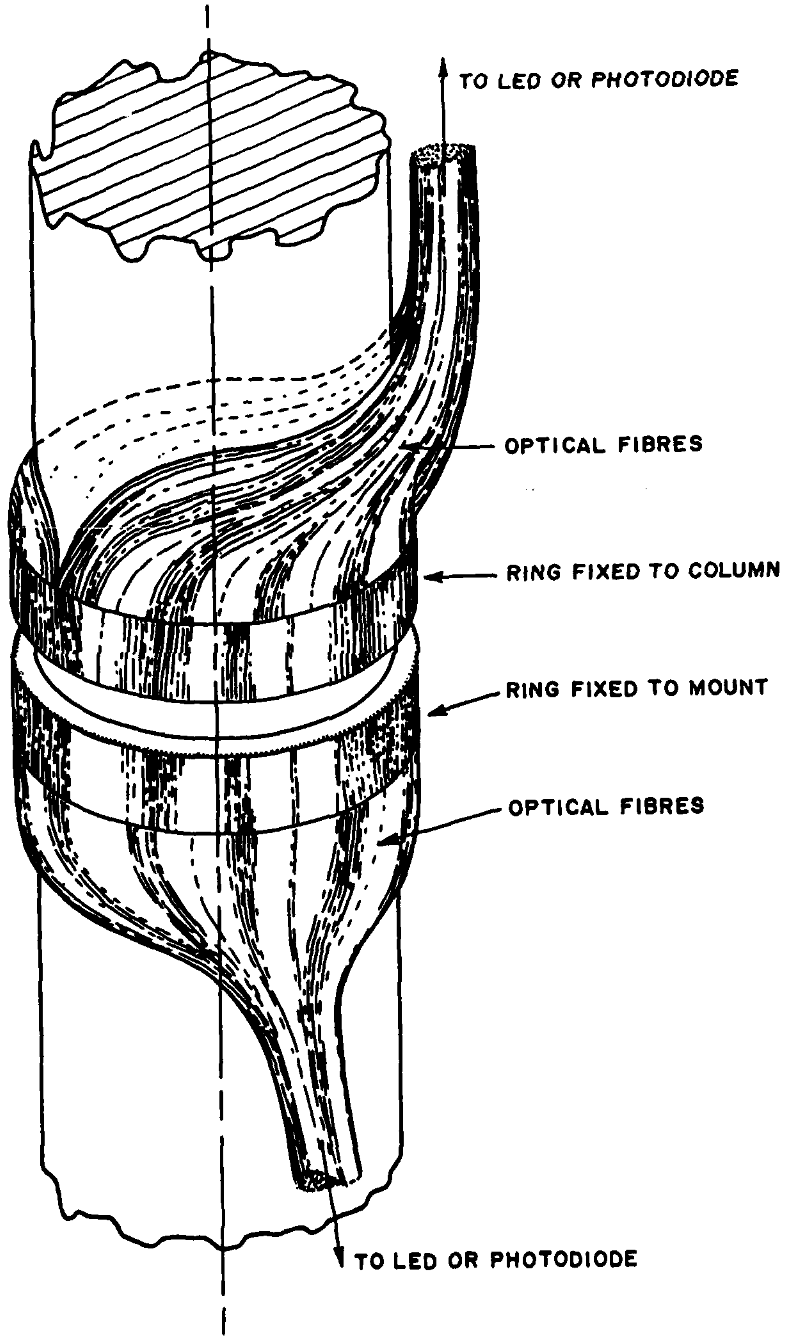
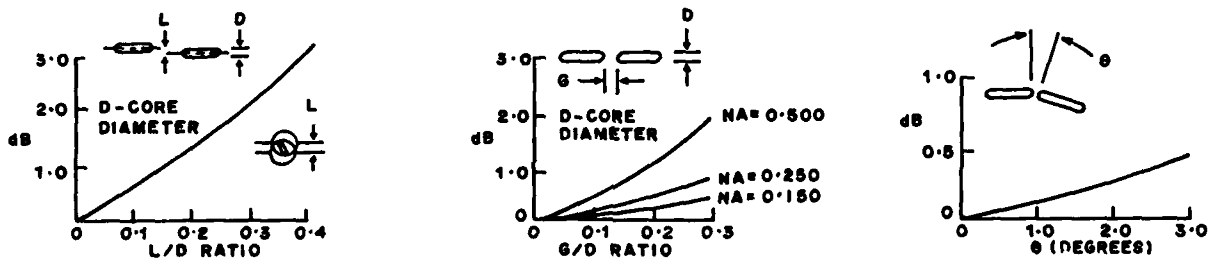


Figure 5. "Ring of Fibres" slip-rings

3.2 Ring of fibres

This type of slip-ring consisted of two rings of optical fibres with the fibres mounted on the outside of the aerial mounting column and lying parallel to the column axis and "face to face". One ring being fixed to the column and the other to a fixed baseplate. At the back of each ring, the fibres are gathered into bundles and led to either a transmitting LED or a photodiode which can be located some distance away in the transmitter or receiver respectively. Thus light transmitted down one bundle of fibres is coupled across the airgap into the second bundle and is detected by a photodiode. The distribution of the fibres round the ring was deliberately allowed to be slightly random to reduce amplitude modulation of the light. The slip-rings are shown diagramatically in figure 5.

Full size and quarter scale models (about 30 mm diameter) were built to investigate different methods of attaching the fibres to the mounting ring. Consideration of the different causes of light loss at the air gap between the two rings as shown in figure 6 led to the use of 0.010 inch stepped index plastic fibres. This allowed tolerances of 0.05 mm (0.002 inch) to 0.1 mm (0.004 inch) for concentricity and "run out" of the rings and the separation between them.



(a) Signal loss resulting from lateral displacement

(b) Signal loss resulting from end separation

(c) Signal loss resulting from angular misalignment

Figure 6. Light losses due to alignment problems

The fibres were located in grooves round the outside of plastic or aluminium rings and parallel to the main axis. The grooves were made on a lathe either by a cutting tool or by a knurling tool of 0.3 mm pitch (85 tpi). The fibres were fixed in position by adhesives or a clear plastic sleeve, and the fibre ends were then cleaned and polished.

The quarter scale model consisted of two lengths of 32 mm diameter plastic rod drilled through the centre and amounted on bearings on a common shaft. The maximum number of 0.010 inch (0.254 mm) diameter fibres that fit round the circumference is given by

$$n = \frac{32\pi}{0.254} = 396 \text{ fibres}$$

and total fibre area is $396\pi \times 0.127^2 = 20\ \text{mm}^2$

and diameter of fibre bundle is $0.254 \times \sqrt{\frac{396}{0.75}} \simeq 6$ mm
(allowing for a stacking factor).

This means that light must be coupled from the LED to a 6 mm diameter bundle with equal illumination over the area and within the acceptance angle of the outer ring of fibres. Similarly light from the bundle must be gathered and concentrated onto the sensitive area of a photodiode. Various experiments were carried out to determine the most suitable combinations of diodes and lenses but it soon became apparent that the light losses were always very large, though not prohibitive.

When the full size slip-rings were considered, it was found that the number of fibres increased to approximately 1700 to 1800 depending on the thickness of the mounting ring and gave a fibre bundle of 12 mm diameter.

This made the matching problem much greater. It was also noted that a large number of the fibres were being damaged by the amount of handling that was required resulting in considerable light loss. This was not always discovered until late in the assembly process when it was difficult to make replacement.

The basic slip-rings were capable of being used to transmit data in either direction but when terminated only one direction was possible. The use of T and STAR couplers to provide alternative methods of termination was a consideration for future development. If more than one channel was required it would be possible to mount the rings concentrically but physical difficulties with the fibre bundles makes this prohibitive. The thought of mounting the rings in tandem provided similar difficulties and it was decided to discontinue further development.

4. ELECTRICAL DESIGN

Each slip-ring requires both a transmitter and a receiver, one of which is mounted on the rotating column and the other on the fixed baseplate. The transmitter converts the signal voltages into electrical power to supply the drive current to one or more LED emitters producing a modulated beam of light. The receiver has to detect the very small current produced by the photodiodes when they are illuminated and amplify it to a level suitable for the following circuits.

4.1 Transmitter

Both LEDs and IREDs are operated in the forward bias mode and the transmitter must be able to supply each of the diodes used, currents in the order of 100 mA at a typical voltage of 1.4 V for GaAs IREDs and up to more than 2.0 V for GaAsP red LEDs. A block diagram of a transmitter is given in figure 7(a). After some experimenting with discrete transistor circuits it was realised that for digital working some of the TTL integrated circuit drivers already had the required output capacity. This led to the use of the circuit shown in figure 7(b) to drive three IREDs in parallel. The 74S140 is a dual quad input NAND gate and 50Ω line driver with a high level output current of 40 mA for each half. For positive logic an inverter is required to reverse the NAND function and gating can easily be arranged at the high NAND input providing an "enable" facility if required. In the circuit R_2 limits the output current and C_1 and R_1 are used to improve the diode current rise time.

4.2 Receiver

The reverse biased photodiodes are operated in the photoconductive mode. Using 5082-4220 diodes with a bias of 15 V, the current rise and fall times are 1 ns and the diode capacitance is 2 pF, noise current is

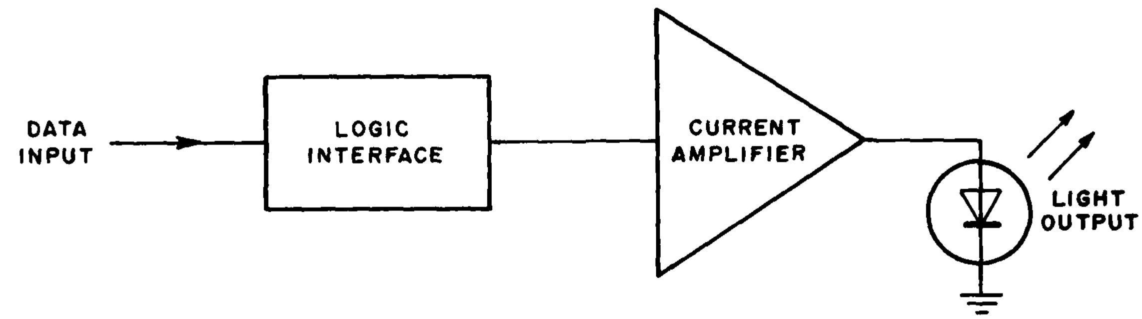


Figure 7(a). Block diagram of transmitter

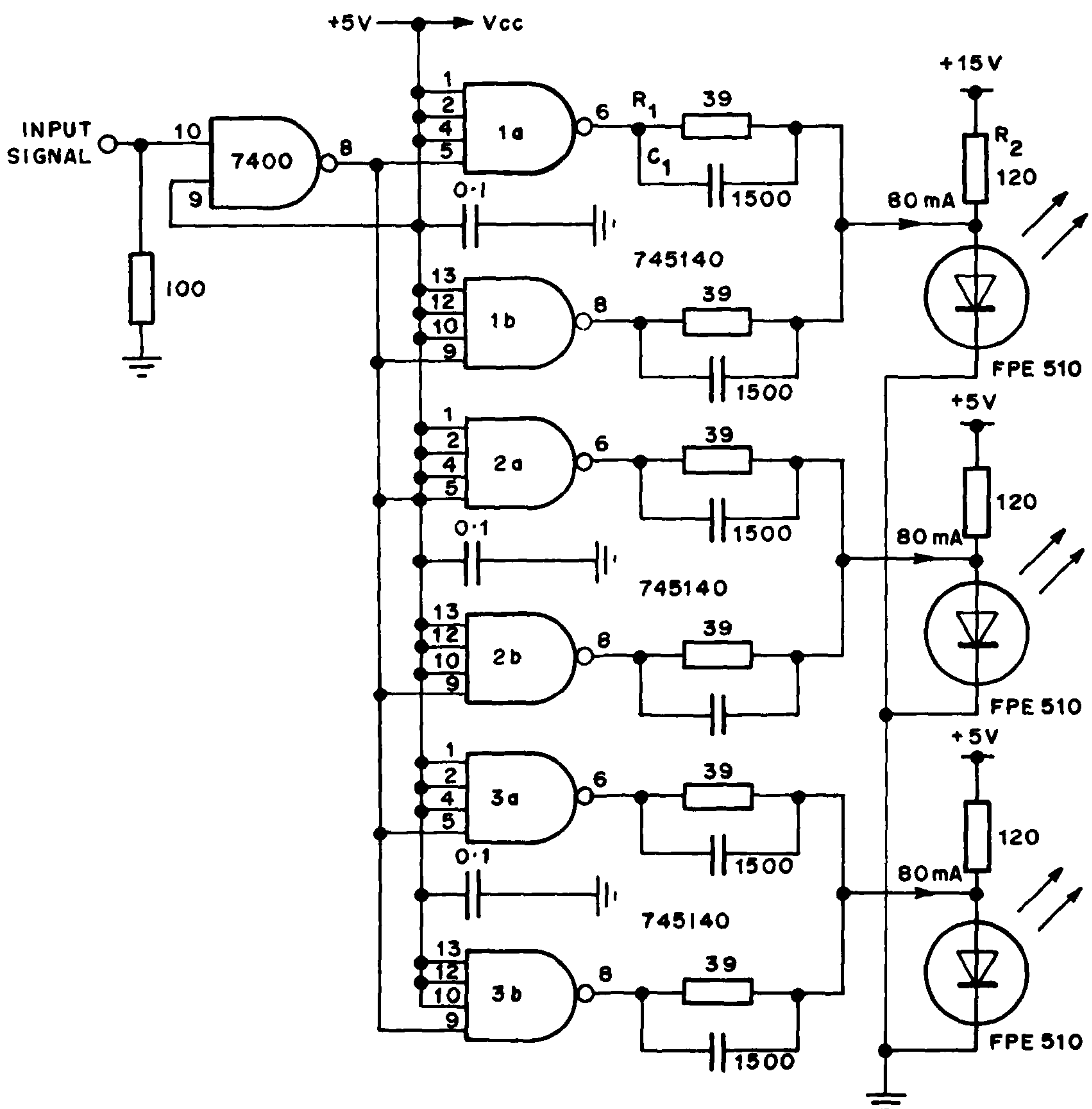


Figure 7(b). Transmitter circuit

negligible. The diodes are connected in parallel so that when one or more of them are illuminated, their sum output current is detected, converted into a voltage and amplified by the receiver. A block diagram of the receiver is shown in figure 8(a).

For the first stage, the obvious approach is to develop a voltage drop across a load resistor R_f and measure this potential with a high impedance amplifier as in figure 8(b). However, this has the following disadvantages:

(a) non-inverting amplifier introduces common mode errors,

(b) ideal current meter has zero impedance whereas R_f may be very large since it determines measurement sensitivity.

(c) changes in input impedance of the amplifier with temperature cause variable loading on R_f and effect sensitivity.

With figure 8(c) we have an ideal current meter with no voltage drop across the measuring circuit since with high open loop gain the input impedance becomes very small. This circuit was initially tried successfully using discrete components but was soon replaced by an integrated circuit version manufactured by Texas Instruments.

The receiver must be ac-coupled to eliminate dc-drift errors in the amplifiers and since all light pulses are unipolar (either ON or OFF) the transmission of a long string of all ONES or all ZEROs in an NRZ format can cause problems in high speed data links. One solution is to code the data so that the dc level is independent of the data. In Manchester or similar code, polarity reverses in each bit period regardless of the information. The transition occurs during the split phase period of the bit centre, positive-to-negative reversal signifies a ONE and negative-to-positive signifies ZERO. This method was tried successfully but it required additional circuits in the transmitter to provide two clock phases and a synchronous clock for decoding at the transmitter. Since the system required twice the bandwidth to encode at the same bit rate, a second method was preferred.

In this method, the transmitter is not modified but a differentiator is used in the receiver to remove the duty-cycle related baseline variations from the data stream. Figure 9(a) illustrates the performance of capacitive and edge-type ac-coupled networks for both 20% and 80% duty cycle pulse trains. If a comparator is used as a level detector to decide whether a ONE or a ZERO is present, it must compare the data stream with a floating reference that tracks the reference of the data stream in the ac-coupled case whereas with the edge type ac-coupled case the baseline is constant. Sufficient recovery time of the differentiator is guaranteed by allowing four time constants after the occurrence of the system rise time t_{rs}.

$$(RC)\ max = \frac{T - t_{rs}}{4} \qquad \text{where T is the minimum bit time}$$

The level detector then requires two thresholds, one above and one below the reference voltage, that is a Schmitt-trigger function with hysteresis whose threshold depends on the detectors output state. This can be achieved by using a comparator with positive feedback as shown in figure 9(b). A further advantage is obtained by using a differential edge-

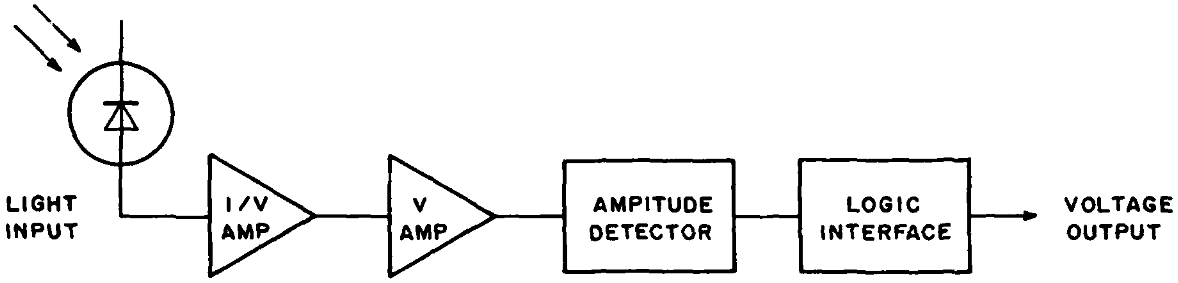


Figure 8(a). Block diagram of receiver

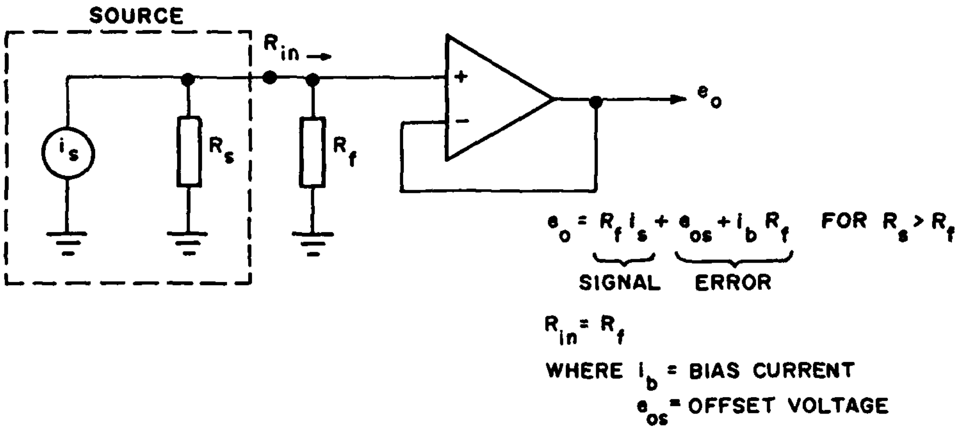


Figure 8(b). High input impedance amplifier

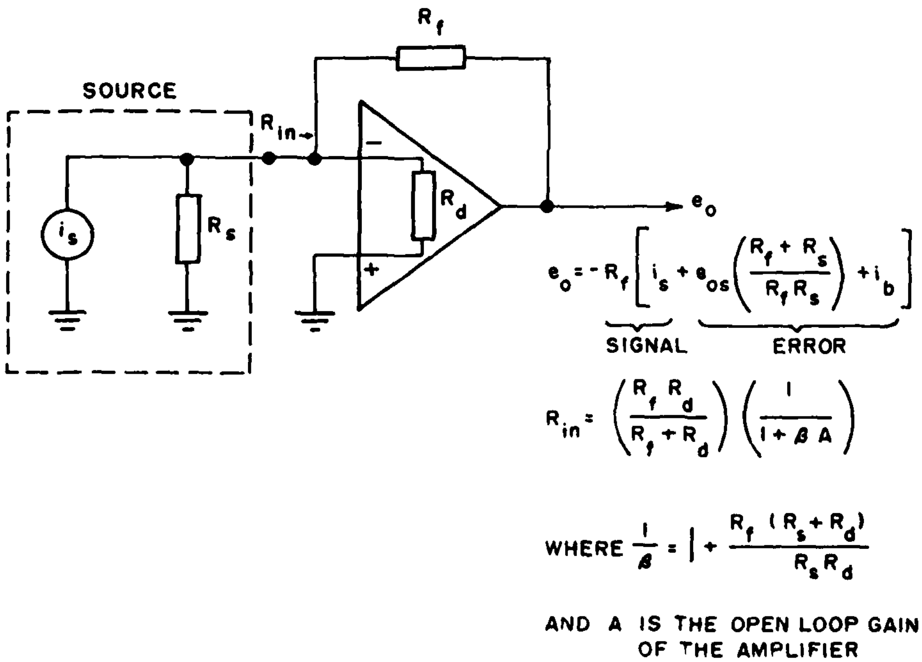


Figure 8(c). Ideal current meter

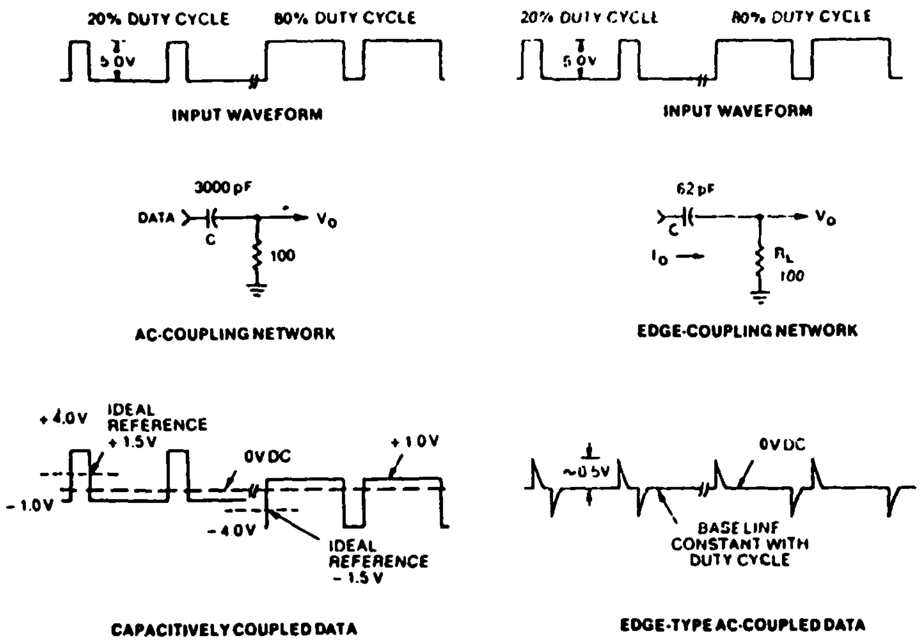


Figure 9(a). Tolerance of duty cycle variations

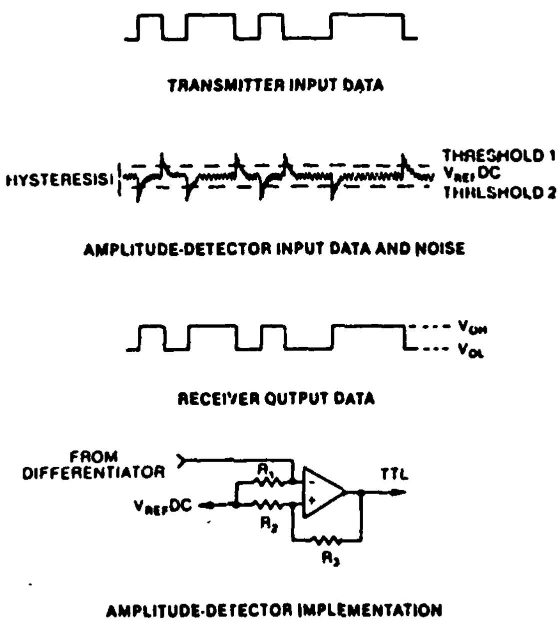


Figure 9(b). Amplitude detector thresholds

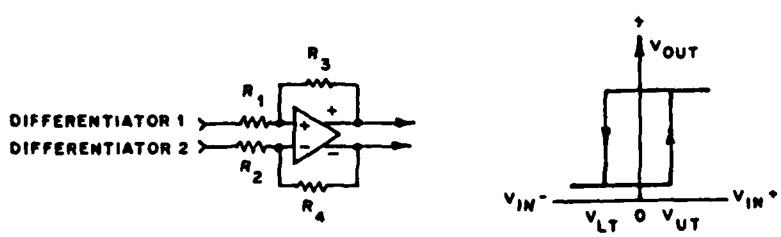


Figure 9(c). Differential comparator as amplitude detector with hysteresis type ac-coupled system which offers common mode rejection, preventing radiation or conduction of extraneous signals into the detector inputs. This is shown in figure 9(c) and the hysteresis is given by:

$$V_{UT} = V_{OH}\left(\frac{R_2}{R_4}\right) - V_{OL}\left(\frac{R_1}{R_3}\right)$$

$$V_{LT} = V_{OL}\left(\frac{R_2}{R_4}\right) - V_{OH}\left(\frac{R_1}{R_3}\right)$$

where V_{UT} = upper threshold voltage

V_{LT} = lower threshold voltage

V_{OH} = output voltage HIGH

V_{OL} = output voltage LOW

and for symmetry $R_1 = R_2$ and $R_3 = R_4$

$$V_{UT} = (V_{OH} - V_{OL})\,\frac{R_1}{R_3}$$

$$V_{LT} = (V_{OL} - V_{OH})\,\frac{R_1}{R_3}$$

and

$$V_{UT} = -V_{LT}$$

Hysteresis is then adjusted so that the background noise spikes do not trigger the level detector.

With the addition of a buffer stage to provide drive for a coaxial or balanced line output as required, the receiver is complete and the final circuit is as shown in figure 10.

4.3 Practical details

The construction of the transmitter caused no problems except for the radiated interference described at the end of Section 3.1. Since the DC power supplies available were of a higher voltage than was needed and to reduce any interference introduced via the power supplies, each unit had its own voltage regulators to provide isolation. However, since the load on the supply varies considerably depending on whether a one or a zero is being transmitted (ie IREDs are ON or OFF), it could be advantageous to use a discrete emitter-coupled differential amplifier with the IREDs as one collector load and a constant current source to the commoned emitters. Thus the logic state of the input determines whether current flows through the IREDS or the other collector's load resistance.

The construction of the receiver is more critical because of the very small signals that are being detected. The photodiodes behave like a current source in parallel with a capacitance which is kept low by device selection and reverse bias. Because the detector is a high impedance source with a small signal output, it is difficult to interface without introducing noise and RFI which degrade signal quality. Consider the following:

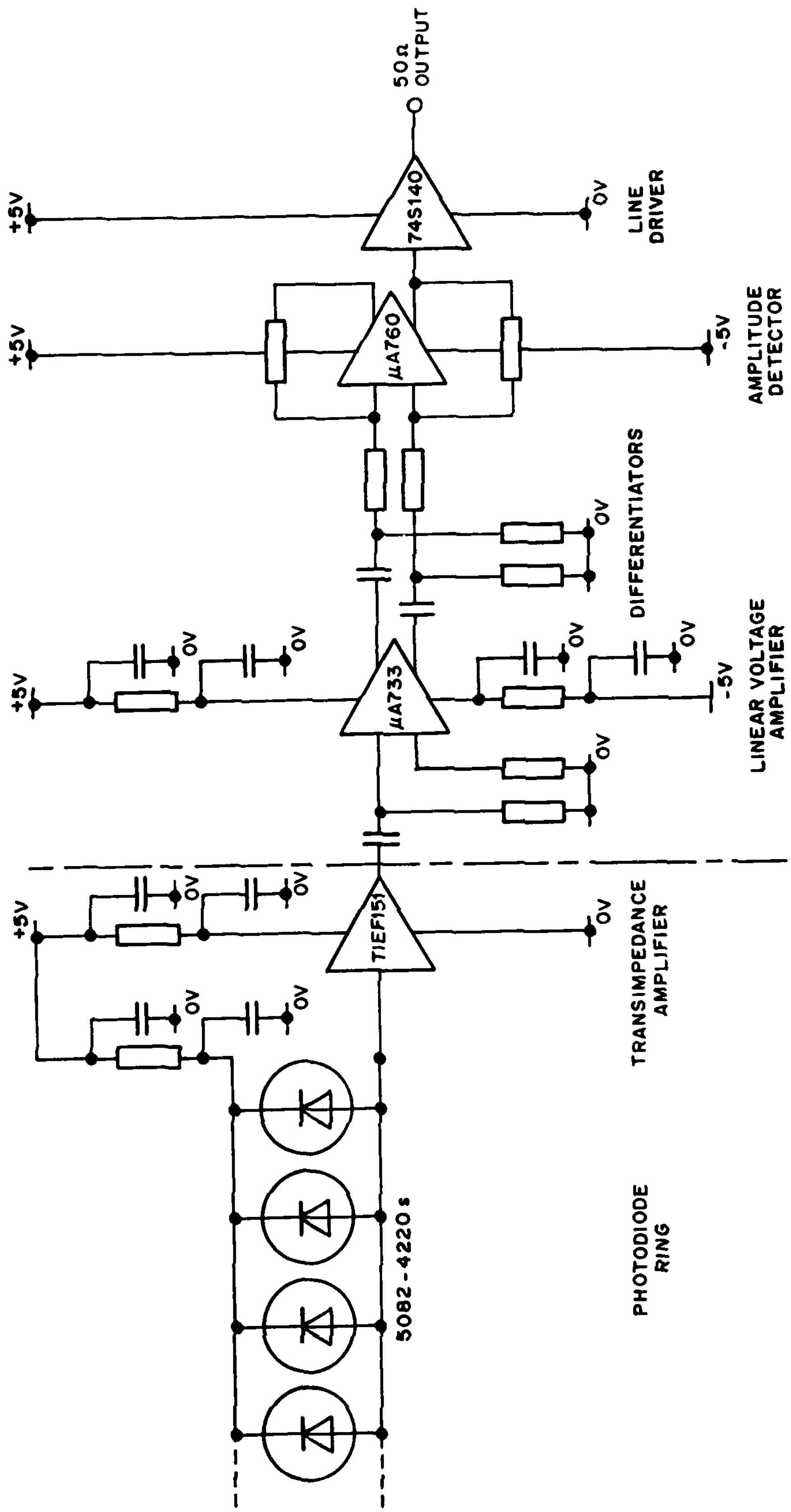


Figure 10. Receiver circuit diagram

photodiode flux responsivity = 0.5 μA/μW
transimpedance amplifier forward transfer impedance = 4 kΩ
voltage amplifier gain = 200 (single side)
level detector trigger voltage = 300 mV

and trigger voltage = $200 \times 4 \times 10^{3} \times I_i$ (amplifier input current)

$$I_i = \frac{300 \times 10^{-3}}{800 \times 10^{3}} = 375 \text{ nA}$$

which is an overall sensitivity of 800 nW per diode.

Suppose that a nearby TTL gate has a voltage change of 3 V in 5 ns

$$I = C\frac{dV}{dt} \qquad C = I\frac{dt}{dV}$$

$$C = \frac{375 \times 10^{9} \times 5 \times 10^{9}}{3} \doteq 0.0006\text{pF}$$

That is, a very small coupling capacitance at the photodiodes is all that is needed to cause the level detector to trigger from a nearby voltage transient (as is found in the transmitter).

However, with the photodiodes on flexible P.C. card with the outside copper plate earthed and mounting this diode ring over a groove cut in the metal block (see figure 3) most interference was removed. Further, decoupling the diode bias voltage at points around the ring and screening the leads to the transimpedance amplifier (which must be kept short) completed the screening.

The rest of the receiver is treated with straightforward printed circuit board techniques with separate supply decoupling for the early stages, localised earthing for each stage and ideally, a metal screen around the transimpedance amplifier. A further improvement may be obtained by reducing the bandwidth of the amplifier stage.

5. COMBINED SLIP-RING

The interface requirements for a second TWS tracking aerial (AEL Experimental) was for four channels as follows:

(a) two channels, one up and one down the mount as a general purpose serial link between the two microprocessors at a 20 K Baud rate;

(b) One up link dedicated for synchronisation of azimuth control;

(c) One down link for special purpose signals from the Video Processor which may comprise 10 MHz pulses.

To satisfy these requirements it is proposed to use a pair of optical slip-rings of the type described in previous sections (but with a smaller diameter)

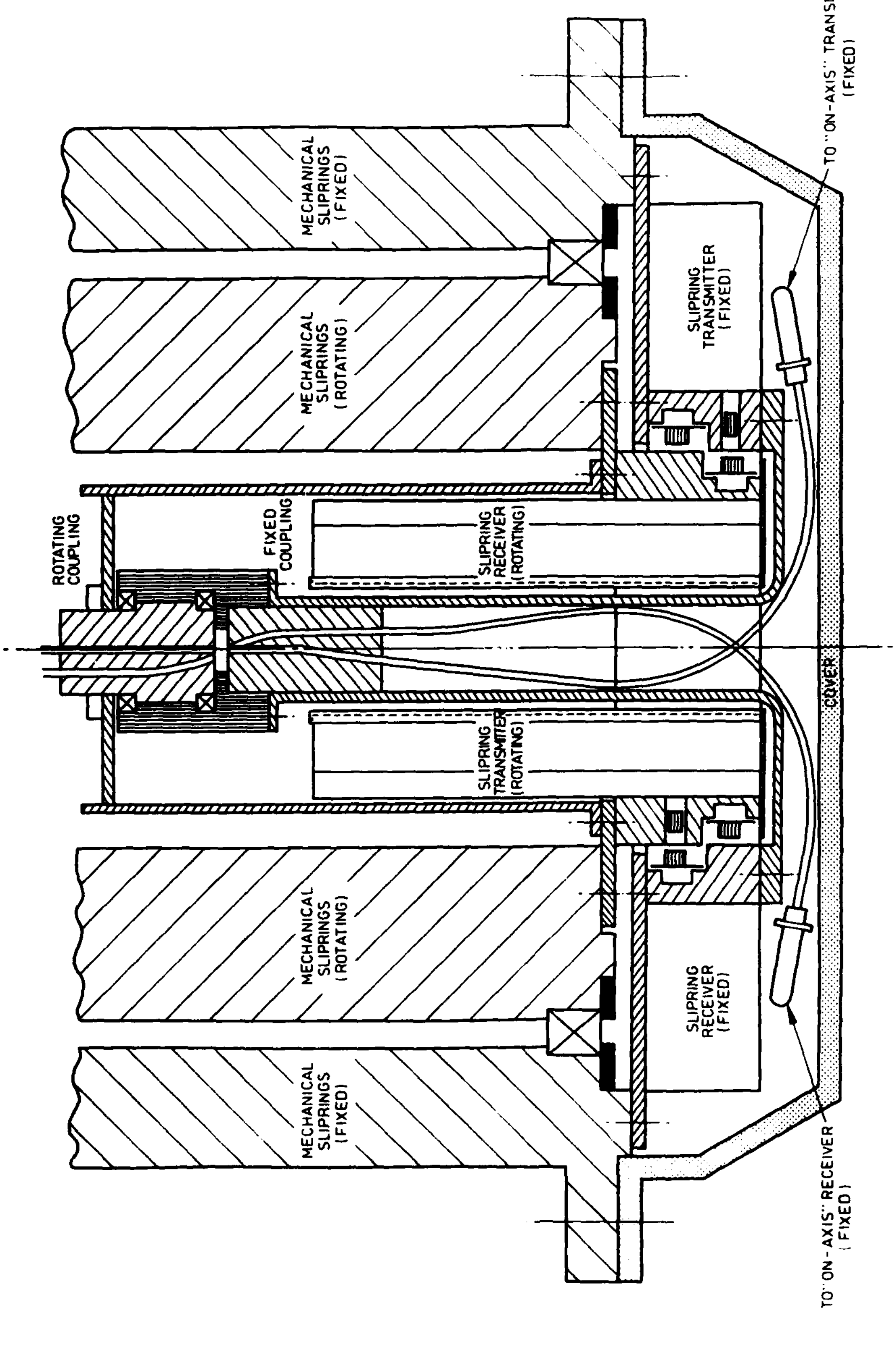


Figure 11. Proposed 4-channel optical coupling

together with an on-axis fibre-optic coupler to be described in a separate Technical Memorandum. A sketch of the 4-channel device is given as figure 11.

The pair of optical slip-rings are mounted on the lower end of the rotating column of the aerial platform adjacent to the mechanical slip-ring assembly and the internal diameter was chosen to accommodate the fibre-optic on-axis coupling. The diameter chosen was 66 mm so that for similar spacing between the photodiodes their number was reduced to 30 on the inner ring. Since the operating frequency of this link is reduced to 20 K Baud, some circuit changes are required. The time constants in both the transmitter pulse shaping networks (see Section 4.1) and the differentiating networks in the receiver are made longer (see Section 4.2). The overall bandwidth of the receiver can also be reduced providing a reduction in noise levels. Further, with the reduced frequency requirement, different IREDs can be used with higher output power. For instance, the LD271 has a radiant flux of twenty times that of the FPE510 with an emission rise time of 1 μs which is now quite adequate. This means a considerable improvement in the signal/noise ratio and the receiver gain can be much reduced for the same trigger level at the voltage comparator. Similarly, the photodiodes can be changed for ones with increased sensitivity but slower response times (this was not attempted with the experimental model since the 5082-4220 diodes were to hand).

The on-axis coupler will be fully described by H. Matthews in another Technical Memorandum and Patent action has been taken so only a brief description is given here. Two optical fibres are placed end to end on the mount axis with a small air gap between them. Two other fibres are placed at a small angle to the axis on either side of the air gap with their ends level with the on-axis fibres as shown in figure 12.

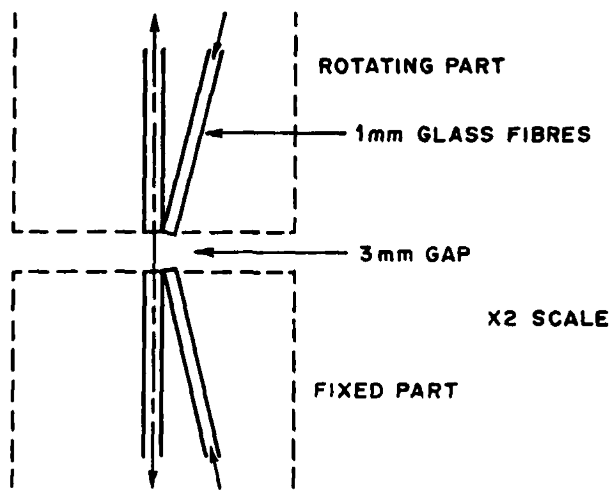


Figure 12. Optical-fibre rotating coupling

Light is now coupled from each angled fibre into the opposite on-axis fibre as shown. The angle to the axis is critical and must be within the acceptance angle of the fibre. In the experimental arrangement, 1 mm stepped-index glass fibres were used with approximately 12° angle between them and with 3 mm separation between each pair. Figure 11 shows the proposed mechanical arrangement for combining the two different types of optical slip-ring.

The transmitters and receivers for each type of optical coupler are basically the same except for the different operating frequency and the need to drive only one IRED and use only one photodiode in the on-axis coupler. One pair of transmitters and receivers for each type of coupling that is fixed to the base of the tracking mount are located in a circle around the outer optical slip-ring. The rotating slip-ring transmitter and receiver are located inside the column adjacent to the slip-ring but the transmitter and receiver for the on-axis coupler can be positioned anywhere that is convenient on the aerial platform.

6. CONCLUSIONS

The optical slip-rings described in this Technical Memorandum are suitable for passing digital data to and from equipment mounted on a rotating aerial platform. The basic design was for fitting to a large diameter column (123 mm) and operating at a frequency of up to 10 MHz. This was achieved but required a large number of rather expensive photodiodes for detecting the signals and the receiver was rather sensitive to noise.

For a lower operating frequency of less than 100 KHz, different IREDs and photodiodes can be used which give considerable improvement to the signal/noise ratio allowing receiver gain to be reduced making it less susceptible to spurious noise signals. This latter version was successfully combined with an "on-axis" coupler to provide a four channel capability for the AEL Experimental aerial mounting.

NOTATION

AEL	Advanced Engineering Laboratory
EMI	Electromagnetic Interference
Ga As	Gallium Arsenide
Ga As P	Gallium Arsenide Phosphide
H	Radiant Incidence
H_T	Total Radiant Incidence
IRED	Infra-red Emitting Diode
I_i	Amplifier Input Current
LED	Light Emitting Diode
n	Number of fibres
NRZ	Non Return to Zero
PIN	Intrinsic P-N Junction
PC	Printed Circuit
RFI	Radio Frequency Interference
R_f	Amplifier feedback Resistance
(RC) max	Maximum Time Constant
STAR	Junction of one to several optical fibres (or fibre bundles)
T	Junction of one to two optical fibres (or fibre bundles)
t_{rs}	System rise time constant
TTL	Transistor-Transistor Logic
TWS	Track-while-scan
V_{LT}	Lower Threshold Voltage
V_{OL}	Output Voltage for logic LOW
V_{OH}	Output Voltage for logic HIGH
V_{UT}	Upper Threshold Voltage

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This technical memorandum describes two different types of optical slip-rings developed for use with a rotating platform which has a column diameter of 123 mm. The preferred type is then combined with an "on-axis" coupling (described elsewhere) for use on an experimental track-while-scan secondary radar system.

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