Preamble

Dissemination of knowledge is one of the objects of the University. Therefore Members of the University and others who submit theses/dissertations for higher degrees are expected to relinquish to the University certain rights of reproduction and distribution.

Moreover, it is recognised that applicants owe a duty to their Departments of study, the Academic Staff and sponsoring bodies for their respective contributions to the research. Within the limits of these requirements, the author's copyright is safeguarded. The author is at liberty to all or part of his thesis elsewhere if he so wishes.

REGULATIONS

1. When submitting a thesis/dissertation for the purposes of a higher degree the applicant shall sign an irrevocable authority in prescribed form appointing the Librarian his attorney with the right to reproduce the thesis/dissertation by photocopy or in microfilm and to distribute copies to those institutions or persons who in the Librarian's opinion require them for academic (as distinct from commercial) purposes.

2. The Librarian in consultation with the appropriate Department of study or sponsoring body shall have the right to refuse to provide copies, or to impose such conditions as he thinks fit on the provision of copies, with the object of safeguarding the applicant's copyright and the interests of the University and the sponsoring body.

If the thesis contains matter of a confidential nature, the author may instruct the Librarian to restrict access to the thesis without the permission of the author or his supervisor for a period not exceeding five years. Such an embargo may be renewed if necessary.

3. These Regulations are subject to requirements of any body under whose sponsorship the research project giving rise to the thesis/dissertation is carried on.
LASER-BASED ACTIVE IMAGING, RANGING
AND TERRAIN MAPPING

BY

S.J. NORTON

A thesis submitted for the Degree
of Doctor of Philosophy at the
University of Surrey

August 1984
Laser-based techniques have been applied to active imaging, ranging and terrain mapping. A review of currently available devices and techniques pertinent to laser-based sensing is presented. An important conclusion drawn is that the science has now matured sufficiently to make laser-based remote imaging a practical proposition.

A major part of the thesis is directed towards the design and development of a prototype short range laser-based terrain mapping system. The pulsed gallium arsenide (GaAs) semiconductor-laser diode-based equipment described in the thesis is capable of determining terrain slopes at distances of up to 25m.

The terrain mapper has been operated successfully, both in the laboratory and also during field trials. Results are presented which, although of a preliminary nature, indicate that the design aims have been achieved.

An extensive investigation has been carried out into the performance of single heterojunction laser-diodes when operated with short duration (ie less than 10ns) current pulses. In this regime laser turn-on effects are found to dominate the laser's performance. Results of both theoretical and experimental studies are presented. Good agreement is found between theory and practice and the performance of these devices operating in this mode is now better understood.
ACKNOWLEDGEMENTS

My thanks are due to Professor J.D.E. Beynon, Head of the Department of Electronic and Electrical Engineering, University of Surrey, for his support and encouragement during my period of research.

I would particularly like to thank Mr. Q.V. Davis and Mr. T.G. Jeans for their help and encouragement during the course of my work. My thanks are extended again to Mr. Q.V. Davis for his help in the preparation of this thesis.

Many useful discussions were held with Mr. P.D.L. Williams and Mr. H.D. Cramp (Racal Decca) to whom I extend my thanks.

The streak camera measurements mentioned in chapter 4 were performed by Dr. D. Hull (MVEE). I should also like to thank Dr. Hull for many helpful discussions regarding the terrain mapping system.

My thanks are also due to other members of the department, both academic and technical, who have given freely their advice and assistance.

The design and construction of the terrain mapper was performed under a contract from the Military Vehicles and Engineering Establishment, Chobham.

Financial support was given by the Science and Engineering Research Council under a CASE award scheme in conjunction with Decca Radar Ltd.
# TABLE OF CONTENTS

## CHAPTER I
**INTRODUCTION, SUMMARY & CONCLUSIONS**

1.1 INTRODUCTION .............................................................................. 15  
1.1.1 Overview ................................................................................. 17  
1.1.2 Laser Rangefinders ............................................................... 26  
1.2 SUMMARY ............................................................................... 30  
1.3 CONCLUSIONS ......................................................................... 33

## CHAPTER II
**REVIEW OF DEVICES AND PROPAGATION CHARACTERISTICS**

2.1 INTRODUCTION ........................................................................... 38  
2.2 LASER SOURCES ........................................................................ 39  
2.2.1 Solid State Lasers ................................................................. 39  
2.2.2 Gas Lasers ............................................................................ 40  
2.2.3 Dye Lasers ........................................................................... 42  
2.2.4 Semiconductor Lasers ............................................................ 43  
2.3 LASER MODULATION ............................................................... 46  
2.3.1 Electro-optic Modulation ....................................................... 46  
2.3.2 Acousto-optic Modulation ...................................................... 47  
2.3.3 Direct Modulation of Laser Power Supply ......................... 48  
2.3.4 Modulation by Absorption .................................................... 50  
2.4 LASER BEAM SCANNERS ......................................................... 50  
2.4.1 Mechanical Scanners ............................................................ 51
3.3.2.3 Effect of Biasing the Laser.............96
3.3.2.4 Time Delay.............................99

3.4 COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS..101
3.4.1 Streak Camera Receiver..........................101
3.4.2 Photodiode Receiver............................104

3.5 SUMMARY.................................................108

CHAPTER IV
LASER-BASED TERRAIN MAPPING SYSTEM

4.1 INTRODUCTION.............................................110

4.2 THE RANGE MEASUREMENT..................................112
4.2.1 Amplitude Modulation................................113
4.2.2 Pulsed Ranging....................................115
4.2.3 The Range Equation...............................116
4.2.4 Noise Sources......................................119
4.2.4.1 Signal Shot Noise.............................119
4.2.4.2 Background Noise............................120
4.2.4.3 Thermal Noise...............................122
4.2.4.4 Excess Noise...............................122
4.2.5 Signal to Noise Ratio............................122
4.2.6 Range Accuracy.................................124

4.3 THE TERRAIN MAPPER HARDWARE..........................125
4.3.1 Terrain Mapper Optical Subsystem..................125
4.3.1.1 Laser Transmitter...........................127
4.3.1.2 Laser Pulse Monitor Photodetector...........129
4.3.1.3 Receiving Optics...............................130
<table>
<thead>
<tr>
<th>APPENDIX No.</th>
<th>PAGE No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>173</td>
</tr>
<tr>
<td>3.1</td>
<td>179</td>
</tr>
<tr>
<td>3.2</td>
<td>184</td>
</tr>
<tr>
<td>3.3</td>
<td>197</td>
</tr>
<tr>
<td>4.1</td>
<td>204</td>
</tr>
<tr>
<td>4.2</td>
<td>209</td>
</tr>
<tr>
<td>4.3</td>
<td>216</td>
</tr>
<tr>
<td>4.4</td>
<td>219</td>
</tr>
<tr>
<td>4.5</td>
<td>226</td>
</tr>
<tr>
<td>4.6</td>
<td>232</td>
</tr>
<tr>
<td>5.1</td>
<td>233</td>
</tr>
<tr>
<td>5.2</td>
<td>234</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIG. No.</th>
<th>Description</th>
<th>PAGE No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Resolution Obtainable from an Active Imager</td>
<td>24</td>
</tr>
<tr>
<td>1.2</td>
<td>Advantages of Range-Gating</td>
<td>25</td>
</tr>
<tr>
<td>2.1</td>
<td>Semiconductor Laser Diode</td>
<td>44</td>
</tr>
<tr>
<td>2.2</td>
<td>Typical Diode Laser Characteristic</td>
<td>44</td>
</tr>
<tr>
<td>2.3</td>
<td>Electro-Optical Modulation</td>
<td>49</td>
</tr>
<tr>
<td>2.4</td>
<td>Acousto-Optical Modulation</td>
<td>49</td>
</tr>
<tr>
<td>2.5</td>
<td>Direct Detection Receiver</td>
<td>59</td>
</tr>
<tr>
<td>2.6</td>
<td>Heterodyne Detection Receiver</td>
<td>59</td>
</tr>
<tr>
<td>2.7</td>
<td>Clear Weather Propagation Characteristic</td>
<td>70</td>
</tr>
<tr>
<td>2.8</td>
<td>Extinction and Absorption Cross-Sections as a Function of Water Droplet Size</td>
<td>73</td>
</tr>
<tr>
<td>2.9</td>
<td>Extinction and Absorption Coefficients as a Function of Water Droplet Size</td>
<td>75</td>
</tr>
<tr>
<td>3.1</td>
<td>Laser Current and Optical Pulse Measurement System</td>
<td>82</td>
</tr>
<tr>
<td>3.2</td>
<td>Laser Diode Current Pulsers</td>
<td>84</td>
</tr>
<tr>
<td>3.3</td>
<td>Predicted Laser Temporal Response</td>
<td>91</td>
</tr>
<tr>
<td>3.4</td>
<td>Transfer Characteristic for Rectangular Current Drive Pulse</td>
<td>94</td>
</tr>
<tr>
<td>3.5</td>
<td>Transfer Characteristic for Half-Sine Current Drive Pulse</td>
<td>94</td>
</tr>
<tr>
<td>3.6</td>
<td>Theoretical Response of Laser with Pre-Bias</td>
<td>97</td>
</tr>
<tr>
<td>3.7</td>
<td>Laser Turn-On Delay versus Drive Current</td>
<td>100</td>
</tr>
<tr>
<td>3.8</td>
<td>Temporal Response of Laser Driven in 1A</td>
<td></td>
</tr>
</tbody>
</table>
3.9 Streak Camera Recording of Laser Output.
   Drive Current 25A, 4ns Duration
3.10 Streak Camera Recording of Laser Output.
   Drive Current 35A, 16ns Duration
3.11 Streak Camera Recording of Shortest
   Observed Laser Pulse
3.12 Transfer Characteristic for Limited
   Bandwidth Optical Receiver
3.13 Transfer Characteristic - Integrated
   Optical Output v Drive Current
3.14 Predicted Laser Temporal Response - Receiver
   Risetime 400ps
3.15 Measured Laser Response - Receiver
   Risetime 400ps
4.1 Terrain Slope Estimation
4.2 Block Diagram of Prototype Terrain Mapper
4.3 Terrain Mapper Optical Subsystem
4.4 Terrain Mapper Electronics Subsystem
4.5 Timing Ramp Waveform
4.6 Laser Trigger Signal
5.1 View from the Laboratory
5.2 Typical Signal Returns
5.3 Range v Elevation Angle Plot of Roof
5.4 Slope v Elevation Angle Plot of Roof
5.5 Horizontal Scan of Roof
5.6 The Terrain Mapper in Operation
5.7 Trials Location No.1
5.8 Trials Location No.2 153
5.9 Trials Location No.3 153
5.10 Plot of Terrain Height v Azimuth v Elevation Beam Pointing Directions 155
5.11 Plot of Terrain Height v Azimuth v Range 155
5.12a Range v Elevation Plot of Terrain 156
5.12b Slope v Elevation Plot of Terrain 156
5.13 Horizontal Scan Through Thicket 158
5.14 Range v Elevation Plots for Terrain Location No.3 159
5.15 Slope v Range Plots for Terrain Location No.3 160
NOMENCLATURE

A = rate equation proportionality constant (cm³/s)
Ar = area of receiving optics (m²)
B = electrical bandwidth (Hz)
B_{opt} = optical filter bandwidth (nm)
c = velocity of light (3.10^8 m/s)
C_{n2} = refractive index structure parameter (m⁻²/³)
f = lens focal length (m)
f_d = Doppler frequency (Hz)
f_m = modulation frequency (Hz)
f_o = galvanometer scanner resonant frequency (Hz)
FOV = receiver field of view (radians)
G = photodetector gain
H = scanner height (m)
H_w = solar irradiance (Wm⁻²/nm)
I_b = ambient light generated photocurrent (A)
I_c = constant current source output current (A)
I_s = peak photodetector output current (A)
i_a = preamplifier input noise current (A)
I_p = peak laser pumping current (A)
i_n² = total mean square noise current
I_{teff} = effective laser threshold current (A)
J_t = threshold current density (A cm⁻³)
I_n = detected optical noise
N_e = electron density in laser cavity (cm⁻³)
N_{eb} = background electron concentration required
for positive gain in laser cavity (cm\(^{-3}\))

\[ N_{\text{eth}} = \text{threshold electron density (cm}^{-3}\) \]

\[ n_i = \text{received optical noise} \]

\[ N_p = \text{photon density in laser cavity (cm}^{-3}\) \]

\[ N_r = \text{no. of resolvable spots (beam scanner)} \]

\[ P_a = \text{drive power for electro-optic modulator (W)} \]

\[ P_{\text{av}} = \text{average optical power (W)} \]

\[ P_{\text{peak}} = \text{peak optical power (W)} \]

\[ P_{\text{sr}} = \text{peak received signal power (W)} \]

\[ P_{\text{sd}} = \text{peak detected signal power (W)} \]

\[ P_t = \text{peak transmitter power (W)} \]

\[ P_{\text{bd}} = \text{detected background power (W)} \]

\[ p = \text{diffuse target reflectivity} \]

\[ q = \text{electronic charge (C)} \]

\[ R = \text{range to terrain/obstacle (m)} \]

\[ R_e = \text{photodetector unity gain responsivity (A/W)} \]

\[ R_{\text{max}} = \text{maximum unambiguous range (m)} \]

\[ R_p = \text{effective photodetector load resistance (\(\Omega\))} \]

\[ s_d = \text{detected optical signal} \]

\[ s_i = \text{received optical signal} \]

\[ \text{SNR} = \text{signal-to-noise ratio} \]

\[ S = \text{local terrain slope} \]

\[ S_w = \text{laser source width (m)} \]

\[ S_h = \text{laser source height (m)} \]

\[ t_a = \text{access time for beam scanner (s)} \]

\[ t_d = \text{laser turn-on time delay (s)} \]

\[ t_{\text{pw}} = \text{pumping current (rect.) pulse duration (s)} \]

\[ T_s = \text{electron lifetime (s)} \]
\( T_p \) = photon lifetime (s)
\( T_r \) = transmittance of receiver optics
\( T_t \) = transmittance of transmitter optics
\( t \) = laser pulse duration (s)
\( t_r \) = laser pulse rise time (s)
\( v_a \) = acoustic velocity (m/s)
\( V_p \) = drive voltage for electro-optic modulator (V)
\( v_p \) = peak photodetector output voltage (V)
\( v_n \) = rms noise output voltage (V)
\( V_o \) = timing ramp output voltage (V)
\( V_{\text{ref}} \) = constant current source ref. voltage (V)
\( v_t \) = target radial velocity (m/s)
\( x \) = excess noise factor
\( \theta \) = terrain/laser beam angle
\( \sigma \) = total extinction coefficient (km\(^{-1}\))
\( \sigma_{\text{scat}} \) = scattering coefficient (km\(^{-1}\))
\( \sigma_{\text{abs}} \) = absorption coefficient (km\(^{-1}\))
\( \sigma_t \) = timing uncertainty (s)
\( \beta \) = spontaneous emission factor
\( \eta \) = detector quantum efficiency
\( \lambda \) = optical wavelength (m)
\( \delta s \) = local terrain slope error
\( \delta \phi \) = angle pointing uncertainty
\( \delta R \) = range uncertainty (m)
\( \Omega_r \) = receiver FOV solid angle (steradian)
CHAPTER 1

INTRODUCTION, SUMMARY AND CONCLUSIONS

1.1 INTRODUCTION

The continuing advancement in the performance and reliability of electro-optic devices and techniques is now allowing laser-based solutions to be applied in a number of new applications. One such application, and one with which this thesis is principally concerned, is that of active imaging.

Active imaging systems use the scattered radiation from a co-operative illuminating source, usually a laser, to form an image of the scene being viewed. The potential advantages of active imaging and ranging in the optical and infrared region of the spectrum, as compared to the radio frequency region, were recognised long before the advent of the laser in the late 1950's. Compared to microwave and millimetre-wave radars, optical systems can achieve beamwidths $\sim 10^4$-$10^5$ times smaller than can be obtained from a similar sized aperture in the radio frequency region. It is this significant increase in angular resolution, ( in addition to the improved temporal resolution achieved by the large available bandwidth ) which makes optical and infrared systems so attractive.

This thesis investigates the use of laser-based
techniques in active imaging and ranging, with particular emphasis on an in-depth case study of a laser-based terrain mapping system developed for an external contractor. The use of an active laser-based system was found to be the only viable solution which could meet the requirements laid down by the contractor.

The design philosophy of the terrain mapper is presented together with some details of the actual construction as well as some preliminary results.

Optical pulses with fast risetimes and short durations are necessary to achieve the required ranging accuracy and resolution. Therefore particular attention has been paid to the performance of the gallium arsenide lasers used in the terrain mapper when they are operated with short duration (less than 10ns) current pulses. The results from both theoretical and practical studies are included.

Since as yet there exist only very few published papers in the field, this introductory chapter begins with a broad overview of the subject. Potential areas of application are outlined, with frequent comparisons being drawn with existing more established technologies, such as microwave and millimetre-wave radars and passive optical/infrared imaging.
1.1.1 Overview

Ever since the advent of radar over 40 years ago there has been a continual research effort, the size of which can be gauged by the large number of scientific papers published on the topic yearly, aimed at improving system performance as more and more applications have arisen. For example, today radars are employed in such diverse areas as meteorology [Rodgers 1983], satellite tracking [Lerch 1970], iceberg detection [Williams 1979] and, of course, in the marine field [Croney 1970]. Most radar systems, however, can usually only detect the presence or absence of an object, or 'target'. Little, if any, information is obtained by the radar about the target's size or structure for which high angular resolution is required. The exceptions here are radars which use a synthetic aperture of large effective size, formed by moving a physically small aperture and applying digital signal processing techniques, to obtain extremely narrow beamwidths [Cutrona 1970]. Their complexity and the need to achieve a significant displacement of the aperture limits the application of such systems mainly to airborne and spaceborne Earth sensing where the motion of the vehicle is used to form the aperture [Bennett 1982].

In many applications, such as in airfield taxiway and harbour/estuary surveillance, and in short-range sensors for robotics vision systems, a target identification, as opposed to a simple detection, capability is often required and this again calls for high angular and range resolution.
The angular resolution of a radar is principally determined by the antenna aperture dimensions and the wavelength of operation. The diffraction-limited beamwidth (\( \Theta_d \)) obtainable from an aperture of dimension, \( D \), at a wavelength \( \lambda \), is given by the well known expression [Silver 1949]:

\[
\Theta_d \approx \frac{\lambda}{D} \quad \ldots \ldots \quad (1.1)
\]

In the microwave region of the spectrum beamwidths of the order of a few degrees can be obtained from apertures of a few metres in extent. It is evident that to increase the angular resolution, and hence, therefore, to improve target discrimination, either the aperture size must be increased or the operating wavelength reduced. Increasing the aperture size is an unattractive solution for two reasons. Firstly, to produce any significant improvement in angular resolution the aperture size would have to be increased by such an extent that it would soon become prohibitively large. Secondly, increasing the aperture size may not always be helpful since the near/far field transition range is thereby increased. In the near field region, which extends up to a range of \( \sim 2.D^2/\lambda \) [Kraus 1950] targets cannot be separately resolved if spaced apart by less than the aperture dimensions.

Hence in many instances the only realistic solution to increasing the angular resolution is to reduce the operating
The choice of operating wavelength below about 1.5 cm (i.e., above 20 GHz) is governed mainly by the presence or absence of a suitable atmospheric transmission window in the spectrum, since the atmosphere is strongly absorbing, via $\text{H}_2\text{O}$ and $\text{O}_2$ in this region. Suitable atmospheric windows exist at 94, 140, 220, and 890 GHz. Most of the work on millimetre wave radar systems to date has centred on the frequency band around 94 GHz owing to the higher output powers which can be obtained from currently available devices [Purcell 1979] at this frequency. Johnston [1979] presents a review of radar systems operating in the millimetre wave band. However, even at these frequencies the angular resolution is not normally sufficient to resolve much target detail. The atmosphere becomes essentially opaque above 890 GHz until the upper edge of the 8-14 micron infrared window (the so-called thermal window) is reached. Although atmospheric attenuation is a rapidly varying function of wavelength in this region, several transmission windows exist through to the ultraviolet region. A more detailed discussion of atmospheric effects relevant to laser radar performance is reserved for the next chapter.

It is a useful exercise at this stage to compare the operation of a laser-based radar with that of a conventional microwave radar. Microwave radars are in widespread use and are fitted to craft ranging from small yachts to large supertankers (which may be equipped with several radar systems). The vertical fan-shaped transmitted beam is
mechanically scanned in azimuth, with a resolution of perhaps 4°. Coverage in the vertical plane, achieved by virtue of the fan shaped beam, may extend to 20° or so. For most targets of interest the transmitted beam will completely envelop the target. In contrast consider a laser radar operating in a similar fashion, also having a fan shaped beam, produced using, for example, a cylindrical beam expanding lens, to exploit the available resolution in azimuth a beamwidth of say, a modest 1mR, may be used. It is obvious that if coverage over the full 360° of azimuth were to be achieved an unacceptably low scanning rate would be required. With approximately 6000 azimuth resolution cells and with the radar transmitting, say 5 pulses per cell to permit integration, a pulse repetition frequency (prf) of 30kHz would be required if the scan rate were to be 1 rev/sec. It is doubtful whether a suitable laser source could be found to operate at such speeds and in any case repetition rates in this region would limit the maximum operating range owing to second-time-around returns. Should resolution in elevation also be required then the prf would become prohibitively high.

This simple example vividly illustrates that in target search applications laser-based systems will generally be unsuitable. However, when the approximate co-ordinates of a target of potential interest are known, having been obtained from a conventional radar say, then with the limited field of view (fov) to be covered a laser-based radar could produce a high resolution scan of the target in a fraction
of a second. Hence laser-based systems of this type will, in general, be used in conjunction with other remote sensors.

There are several possible transmitter/receiver configurations which could be adopted. A receiver having a single detector whose field of view is scanned in unison with the transmitted beam is one obvious possibility. Alternatively various solid state detector arrays are available (both 1 and 2 dimensional) which could be used to form a 'staring receiver' requiring no mechanical scanning. This configuration could be used in conjunction with either a scanned collimated transmitter beam or a 'floodlight' beam which covers the total field of view of the receiver.

However, combining a laser illuminator with a conventional passive imager, although improving the performance of the passive imager under conditions of low ambient radiation, does not normally allow range information to be extracted. This highlights a significant advantage of active imaging as compared to passive imaging. The ability to obtain range information, which is of course in itself a considerable advantage when one considers the problems associated with deriving range information from passive images [McVey 1982], can also allow range-gating to be performed. Range-gating enables target contrast enhancement to be achieved. Consider, for example, a target situated against a background of similar visual appearance. Viewed with a passive imager the target contrast will be low and the target may not be perceivable. An active imager with a
Range-gating facility can selectively 'open' the receiver to view any required range resolution cell. The background is now effectively removed and the target appears in isolation from its surroundings. With the high switching speed obtainable from electro-optic devices, range-gates of only a few metres in extent are easily achievable.

Range-gating can also be used to good effect to improve contrast in conditions of poor atmospheric visibility. If artificial illumination is used in such conditions then considerable backscattering directly into the receiver will occur from the atmospheric precipitation whenever the dominant attenuation mechanism is scattering. Such conditions occur, for example, in mist and fog. The use of an illuminating source with a passive imager would do little to improve the target contrast. The situation is similar to the effect observed when driving a car through fog; switching the headlamps to main-beam (i.e. increasing the illumination) just results in a greater level of backscattered light from the fog, no increase in visibility occurs. An active system with a range-gate can, however, exclude the large atmospheric backscattered signal. Given that sufficient of the transmitted beam reaches the target through the precipitation (beam spreading and absorption will both cause the beam to be attenuated) an improvement in target contrast will be achieved.

The merits of active imagers and the improvements which can be gained by using range-gating were first investigated in some experiments which formed a preliminary
part of the present project. Details of the active imager which was designed are briefly described in Appendix 1.1, however, the results obtained from the imager are sufficiently interesting to warrant inclusion here of Figs.1.1 and 1.2.

Fig.1.1(b) shows the result of operating the imager against a clock face situated 85m from the imager. This Figure clearly demonstrates the resolution which can be achieved with an active imager.

Fig.1.2 illustrates the advantages which can be achieved by using a range-gated receiver. A hardboard cut-out of a ship, Fig.1.2(a) measuring 58cm by 25cm was situated at a range of 24m from the transceiver, the angle subtended being 1.4°.

To show the effects of poor target/background contrast a 0.9m by 0.6m board of the same material was placed a further 6m away. As can be seen from Fig.1.2(b) the profile of the target is hard to distinguish by eye.

With the background board now removed a semi-transparent screen was placed at a range of 7m. A photograph of the scene is shown in Fig.1.2(c). Again the target profile is not readily discernable by eye.

With both the background board and screen in place, an image of the target was obtained using the imager, Fig.1.2(d). Allowing for the poor line registration caused by the method of scanning, the features of the target are easily recognisable.

Although laser-based imaging systems are still very
Fig. 1.1 Resolution obtainable from an active imager
a) Target profile

b) Target and low contrast background

c) Target plus intervening clutter

d) Image taken with the active imager

Fig. 1.2 Demonstration of the advantages of range-gating
new, more simple laser rangefinding devices have been in existence for over 20 years. It is worthwhile at this stage of this introduction to summarise briefly the state of the art of laser rangefinding since much of it is of application to laser-based imaging systems.

1.1.2 Laser Rangefinders

Typical early laser rangefinders used pulsed lasers having ruby (694.3nm wavelength) as the active medium with ranging up to 10km and range accuracies of a few metres being readily achievable [Vollmer 1967]. The low conversion efficiency of ruby requires that a large pumping energy of several hundred joules be supplied for every pulse transmitted, making a compact design difficult. Today the more efficient (2% compared to ruby's 0.05%) neodymium doped yttrium aluminium garnet (Nd:YAG, 1.06μm) crystal, which also has superior mechanical properties, is now widely used in many military rangefinders [Coffey 1972]. These commercially available rangefinders can be very compact, being similar in appearance to a pair of binoculars. A direct range readout using light emitting diodes (LED's) is normally presented to the operator through one of the eyepieces. A range-gate can usually be implemented to distinguish between multiple returns. Output pulse powers are usually in the region of 0.5-2MW., with pulse durations of a few tens of nanoseconds. Repetition rates are generally low, being of the order of a few pulses per second. In addition to military applications solid state laser
rangefinders have also been used for atmospheric pollution monitoring [Uthe 1982], and airborne sea-depth profiling [Kim 1977].

Nd:YAG rangefinders present a hazard to the unaided eye at ranges up to 0.5-1km, and the problem is compounded if viewing aids such as binoculars and telescopes are used to view the beam inadvertently. Under illumination from a coherent source the focusing action of the eye is such as to concentrate incoming light onto a very small area of the retina, producing a high power density capable of inflicting damage even at only relatively low power levels. However, at wavelengths of above 1.4\mu m the corneal layer of the eye becomes essentially opaque, thus preventing the laser radiation from reaching the highly sensitive retina. The solid state holmium laser, operating at a wavelength of 2.06\mu m, enables an increase of $2 \times 10^3$ in incident power to be tolerated at the eye compared to an equivalent Nd:YAG system. This allows for eye-safe operation at virtually any viewing range. Holmium laser radiation is, however, also transmitted by optical viewing aids (silica glass is transmissive up to approximately 4\mu m) and this fact can considerably reduce the safe operating range. A holmium based hand-held eye-safe laser rangefinder has been reported [Forrester 1981] which has a similar operational performance to Nd:YAG, with a slightly enhanced performance in low visibility conditions, owing to the reduced atmospheric scattering at the longer wavelength.

The holmium laser has the longest operating wavelength
of the solid state lasers. For longer wavelength operation, where the benefits of eye-safe operation and improved propagation characteristics in poor visibility occur, rangefinders based on gas lasers, notably the carbon dioxide (CO$_2$) laser operating at 10.6μm, are used. The high spectral purity which can be obtained from gas lasers enables the use of either direct or heterodyne detection schemes. Using a heterodyne based receiver increased detection sensitivity can be obtained as compared with direct detection especially at the CO$_2$ laser wavelength. The use of coherent detection enables Doppler shifts to be determined [Hughes 1973] and also opens up the possibility of the use of pulse compression techniques [Oliver 1979]. A CO$_2$ heterodyne laser rangefinder described by Hulme [1981] used a frequency chirp waveform to modulate, via an acousto-optic modulator, a 3-4W continuous-wave laser. A surface acoustic-wave filter compressed the 4microsecond transmitted pulses to approximately 100ns on reception. When operating against natural targets ranges of a few kilometres, with range accuracies of a few metres were achieved, with integration times of a fraction of a second.

A pulsed CO$_2$ coherent laser rangefinder has been described by Cruikshank [1979]; ranging to 32km was achieved with a 400kW 1microsecond duration pulse. A direct detection pulsed CO$_2$ laser rangefinder producing pulses of 300kW (peak) and 60ns duration with ranging to 5km, is described by Taylor [1978].

The helium neon c.w. gas laser, which operates at a
wavelength of 632.8nm has also been used for ranging. Such lasers have found application in civilian surveying, using retroreflective targets and simple c.w. modulation. Ranging to many kilometres, with accuracies of a few millimetres, has been achieved, although to attain this level of accuracy the velocity of propagation must be known to at least this precision [Earnshaw 1967]. Long range operation of helium neon systems with non co-operative targets is not generally possible owing to the degredation of signal-to-noise ratio which would occur with a direct detection receiver. The helium neon laser also has the disadvantage of operating in the visible region and can, therefore, present an eye hazard.

By virtue of its low cost, small and rugged construction and simple power supply requirements the semiconductor laser is ideal for many short range laser radar applications. Typical applications to date have included airborne terrain profilers [Mamon 1978] surveying [Rando 1982], and cloud-base measurement [Milton 1972].

A small number of papers, mainly describing experimental active imaging equipment, have appeared recently in the scientific literature.

Hull and Marcus [1978] have described a proposed coherent CO₂ laser-based system capable of target search (within a limited field of view), identification and automatic fire control for air-to-ground missile deployment. In the target search mode the laser will run c.w. and the output beam will be scanned over a 20°-30° field-of-view.
Once the target has been acquired the system will change to a pulsed mode of operation to make possible accurate target range estimation and also to obtain contrast enhancement by range-gating. A test-bed version of the system using a Q-switched laser operating at 25kHz prf and an average power of 1W has been used to image various targets at ranges of up to 3km. A 1Hz frame rate and a FOV of 128x128 elements was used.

Another CO$_2$ based imaging system has been described by Courtenay [1975]. Using a 32x24 element FOV receiver and a prf of 1Hz images are presented of vehicles at a range of 200m.

Lamberts [1976] reports on a Nd:YAG laser active imager. A resolution, determined by the divergence of the scanned laser beam, of 0.17mR was achieved. A 'staring' receiver was used to obtain images at ranges of up to 1.5km.

1.2 SUMMARY

Following on from the overview presented above chapter 2 presents a review of devices and propagation characteristics relevent to optical radar systems.

During the design of the terrain mapper system described in chapter 4 it was observed that the performance of single heterostructure laser diodes was significantly modified when driving these devices with short (less than 10ns) duration current pulses. As no relevant previous work covering this area could be found in the scientific literature a study into the observed effects was initiated.
An automated measurement system is described which has been used to record both the pumping current waveform and the resulting laser output from a number of commercially available laser diodes. In addition high temporal resolution (10ps) measurements were performed using an electro-optic streak camera optical receiver.

A computer program has been developed which solves the coupled rate equations describing the temporal behaviour of the laser. The simulation allows any pumping current waveform to be specified, as well as the parameters of the laser, and produces a graphical output of the photon and electron densities within the laser.

This program has also been used to generate drive current versus optical output transfer characteristics for specific driving current waveforms enabling output power predictions to be made, in particular, for short duration pulses. The idea of an effective threshold current, dependent on the current pulse waveshape and duration has been introduced.

During the course of these measurements the laser's temporal response was observed to vary as a function of the probe detector position within the laser beam. Some temporal response beam profiles illustrating the effects observed are given in Appendix 3.1.

Chapter 4 describes the design and construction of a short range GaAs laser-based terrain mapping system. GaAs laser diodes are available for operation either in cw or pulsed mode. A comparison is made between the two forms of
modulation, with the pulsed mode of operation being found to be considerably superior for this particular application.

An error analysis (Appendix 4.1) has been performed which enables the terrain slope measurement error to be related to the range and angle pointing uncertainties of the instrument.

For short ranges of operation the configuration of the optics needs to be carefully considered. Firstly, the receiver may be defocused at short ranges, resulting in a reduction of the detected signal. Secondly, any obscuration of the receiving aperture, which could occur, for example, if a coaxial optical arrangement is used, can again significantly reduce the detected signal level. The effects of receiver defocusing and obscuration are discussed in Appendix 4.4.

Target reflectivity is an important factor in determining the magnitude of the received signal. In addition the relative orientation of the scattering surface will also affect the received signal level. In order to gain experience of the likely variations which would occur in a typical terrain mapping environment a fairly comprehensive experimental study was performed. An automated computer controlled measurement system has been developed to obtain target reflectivity versus aspect angle data for a variety of both natural and man-made materials. A description of the measurement system and a sample of the results obtained are presented in Appendix 4.2.

The terrain mapper obtains digital range information
by measuring the time-of-flight of the 2W peak power transmitted laser pulse using a linear ramp timing waveform. A analogue-to-digital (A/D) convertor provides a 10bit range word. For a maximum operating range of 50m the quantisation level of the A/D convertor corresponds to a range uncertainty of 5cm.

The terrain mapper is controlled by a small desktop computer which is also used to store the range data. This data is then transferred onto the University's main computer system for processing and display.

Both transmitter and receiver are scanned in unison over a maximum field of view of 10° by 10° with an instantaneous FOV of 8mR.

Results obtained from the terrain mapper are presented in Chapter 5. These include some results obtained during field trials of the equipment.

Wherever possible material not crucial to the comprehension of the topic under discussion is placed in the Appendix section at the rear of this thesis.

1.3 CONCLUSIONS

The main conclusion that can be drawn from the work presented in this thesis is that laser-based sensing can now be considered to be a viable and practical solution to many remote sensing applications. Several new sensor applications which are only made possible by the use of laser-based techniques have now become feasible, the terrain mapper equipment described in this thesis is a case in
The principal features of active imaging and ranging systems can be summarised as follows:

1) A high angular resolution is readily achievable from apertures of small physical size permitting targets to be identified.

2) An inherently large bandwidth is available permitting accurate determination of a target's range and also providing good range resolution.

3) Image contrast enhancement is possible by range-gating the scene being viewed.

Perhaps the biggest attraction of laser-based remote sensing systems is their high angular resolution. For example, at the CO₂ laser wavelength of 10.6μm and with an aperture of 10cm a diffraction limited beamwidth of 0.1mR can be achieved. Of necessity the narrow solid angle covered by the beam precludes laser radars from most target search and acquisition roles.

In order to obtain range information the laser source must be modulated in some way. For direct detection receivers a low duty cycle, high peak-power waveform makes the best use of the square-law response of optical photodetectors. More sophisticated modulation techniques may be considered if a coherent detection scheme were incorporated. Now, as in the radio frequency region, a linear detection process operates and the detection
performance is independent of the temporal characteristics of the transmitted waveform. Most of the modulation methods employed in the radio frequency region can be applied to coherent laser radar systems.

The pulsed semiconductor diode laser is an ideal choice for many short range applications. Its performance, however, should be carefully examined if current drive pulses with durations of the order of the spontaneous relaxation time of the device are used. In this regime laser turn-on effects dominate the lasers performance. Depending on the current pulseshape the lasers threshold current is found to increase with reducing pulsewidth. This results in a decrease in the expected optical output power. Expressions relating this 'effective threshold' current to the manufacturers quoted threshold current are given in chapter 3.

The use of a bias pulse appears to be the most promising technique for increasing the optical output power when using short duration drive pulses. The optical pulse risetime is an important parameter when considering the timing accuracy which can be achieved by a ranging system. The optical flux risetime is always considerably faster than the pumping current risetime, with typical measured flux risetimes in the region 100-200ps.

Although not normally observed when viewed with a photodiode and oscilloscope considerable fine structure is present within the optical pulse as is predicted from theory.
The low duty cycle which results when generating pulses of the order of a few nanoseconds duration at rates of a few thousand pulses per second can enable the maximum peak power rating (quoted for a 200ns duration pulse) to be exceeded. For a given peak power this allows a device with a lower threshold current, and therefore a smaller emitting facet, to be used when pumping with short duration pulses. This in turn results in a brighter source and a smaller illuminated area at the target.

Terrain mapping using laser-based techniques has been demonstrated to be a viable and practical proposition. An examination of the factors governing the slope measurement error (Appendix 4.1) shows that for a scanner height of 2m a range accuracy of approximately 15cm and an angle pointing uncertainty of 2 arc minutes are required for terrain slope estimations in the range 5-25m.

A pulsed semiconductor laser rangefinder is found to be the best means of obtaining the range information. The use of optical pulses of only a few nanoseconds duration, although requiring care in optimizing the drive current pulse, are found to be most suitable.

A coaxial optical arrangement is generally unsuitable if narrow field of view's and short range operation are simultaneously required. The resulting blockage of the receiving aperture causes a complete loss of signal to occur at close ranges. Receiver defocusing which occurs at close ranges has the beneficial effect of reducing the dynamic range of the received signal.
Deriving the targets range from a leading-edge timing circuit provides satisfactory ranging accuracy. The timing uncertainty caused by variations in the received signal level is determined by the receiver bandwidth. The ranging accuracy may be improved, for applications requiring a higher degree of accuracy, by either increasing the receiver bandwidth or incorporating a 'constant fraction' type discrimination timing circuit.

The use of a laser pulse monitoring circuit provides a well defined fast risetime pulse to initiate the time-of-flight measurement. Triggering directly from the transmitted pulse removes any errors which could result from the variable laser turn-on delays (chapter 3).

Preliminary results obtained from the terrain mapping system, both in the laboratory and during field trials have clearly shown the potential of the instrument. So much so that the organisation sponsoring this work has extended their funding for a further 2 years.
CHAPTER II

REVIEW OF DEVICES AND PROPAGATION CHARACTERISTICS

2.1 INTRODUCTION

This chapter briefly reviews the currently available devices and techniques which may be employed in an optical radar system, and also discusses atmospheric effects pertinent to laser radar operation.

Considerable advances have been made during recent years in both laser and detector technology. Many improvements and refinements have been made as devices have slowly emerged from the laboratory environment into products suitable for use in commercial equipment. It is primarily these developments which now make laser-based radar systems a practical proposition. A discussion of the capabilities and characteristics of optical detectors and laser sources, together with a review of modulation and scanning techniques forms the first half of this chapter.

With the possible exception of satellite based systems careful consideration must be given to the effect of the atmosphere on the overall system performance. The atmosphere, with its continuously changing characteristics, governs several system parameters. The transmitter wavelength, for example, should be chosen to coincide with a spectral region of acceptable attenuation for the desired operating range. Other effects such as atmospheric
turbulence, signal depolarisation and dispersion may, depending on the type of system, also have a significant effect on performance.

2.2 LASER SOURCES

2.2.1 Solid State Lasers

In their simplest form solid state lasers comprise of a crystalline rod (typically 5mm in diameter by 50mm in length) mounted in a resonant cavity and an optical pump source. The active medium is raised to a state whereupon coherent emission can occur by means of a flash lamp. The spectral emission from the lamp is such that the absorption bands of the medium are excited. Owing to interactions between the many modes which can be supported by the laser medium and cavity the temporal output of such a laser would appear as a random noise like burst of optical power. To control the temporal output of the source more sophisticated modulation methods are required; these are outlined in section 2.3.

Early solid state lasers were based on ruby but owing to that material having a very low conversion efficiency (that is electrical pump power input to optical power output), it being approximately 0.05%, Nd\(^{3+}\) doped yttrium aluminium garnet (Nd:YAG), whose efficiency is of the order of 2% is now widely used. The emission wavelength of Nd:YAG is 1.06µm which can present problems with eye safety even at ranges greater than 1km. The ability of laser light to
inflict damage on the eye diminishes greatly beyond a wavelength of about 1.4\textmu m and consequently much interest has been focused on \textit{Er}^{3+} doped glass (1.54\textmu m) and more recently \textit{Ho}^{3+} doped yttrium lithium fluoride (2.06\textmu m) lasers.

2.2.2 Gas Lasers

Unlike the solid state laser the gas laser can easily be operated in either pulsed or continuous wave (c.w.) modes. The active medium, in this case a gaseous mixture, is excited by some form of electrical discharge. Extremely high spectral purity is possible from gas lasers with emission linewidths in the kilohertz region or lower being achievable. The good spectral quality of gas lasers makes the use of heterodyne detection schemes possible.

The carbon dioxide laser [Duley 1976] has an emission wavelength of 10.6\textmu m ( P(20) transition ) and can be operated in either pulsed or c.w. modes. In order to achieve high output pulse power it is necessary to operate with the gas mixture at high pressure. Discharges through gases at high pressure can lead to localised breakdown and arcing and this proved to be a problem with early \textit{CO}_2 lasers. Beaulieu [1970] proposed a configuration comprising of a series of pin electrodes (anode/cathode) and a single flat electrode which were transversely excited. This arrangement is commonly referred to as the TEA (Transversely Excited Atmospheric) \textit{CO}_2 laser.

Modifications to this basic design have since occurred, notably the addition of a pair of thin 'trigger
wires' between the main electrodes which are now precisely shaped to give an extremely uniform discharge along the complete cavity length. The gas mixture is typically formed from the following constituents \(	ext{CO}_2\):\text{N}_2:\text{He}\), with the approximate ratios of the constituents being 0.8:1:7 [Duley 1976-Chapter2]. A population inversion is created by firstly pre-ionizing the gas with a small discharge between the trigger wires and the cathode and then connecting the main storage capacitor (25kV, 2.5J) across the electrodes. The resulting characteristic TEA \(	ext{CO}_2\) laser pulse comprises of a high intensity (250kW from a 250mm laser cavity) short duration (60ns) pulse followed by a low intensity tail lasting some microseconds [Manes 1972]. Such lasers are commercially available with sealed off tubes yielding in excess of 1 million shots at pulse repetition rates of 2pps.

The high efficiency of the \(	ext{CO}_2\) laser enables c.w. powers into the multi-kilowatt region to be generated. Although efficiencies can be as high as 30% at low power levels, values of 10% are more common when operating the laser at rated power [Roberts 1967]. Typical c.w. power levels used for active imaging and rangefinding applications are in the region of a few watts, which can be conveniently obtained from the recently developed waveguide \(	ext{CO}_2\) laser [Bridges 1972]. These physically compact lasers have a narrow cavity cross-section (typically 1mm²) and operate near atmospheric pressure with low d.c voltage (100v) or radio frequency discharges. Sealed off operation of several thousand hours is obtainable from commercially available
The helium neon c.w. laser [White 1962] operates in the red region of the visible spectrum at a wavelength of 632.8nm. Typically output powers of 0.5mW to 25mW can be obtained from reasonably compact tubes using high voltage direct current excitation of the gas mixture. The use of helium neon lasers for ranging is limited to applications where a large received signal can be obtained, as for example occurs when retroreflective targets are used.

Other principal types of gas lasers include; rare gas ion lasers - argon(0.3-0.5µm), krypton(0.3-0.8µm), metal vapour lasers - helium cadmium(0.3µm), pulsed nitrogen (0.3µm) and excimer, such as xenon fluoride (0.3µm), and the infrared HF/DF (2.6-4µm) and carbon monoxide (5µm) lasers. Although employed in some atmospheric monitoring systems these lasers, for various reasons, are not generally suitable for laser radar applications.

2.2.3 Dye Lasers

A unique feature of dye lasers [Schafer 1979] is their ability to produce a continuously tunable output wavelength of 2-3 octaves. The laser comprises of an organic dye in solution which is optically pumped, usually by an ion or Nd:YAG laser. The wavelength range is dependent on the dye used, with operation limited to the visible and near infrared region. Both c.w. (1watt typical) and pulsed (greater than 1MW, 5ns pulsewidth, 200pps) lasers are available.
Physically the lasers are very bulky, requiring sophisticated control systems, and with operation limited to the visible/near infrared dye lasers have not, apart from specialised atmospheric monitoring, been used in laser radar systems.

2.2.4 Semiconductor Lasers

Semiconductor diode lasers [Thompson 1980] comprise of a rectangular cross-section p.n. stripe junction (see Fig.2.1) with cleaved and polished ends to form a Fabry-Perot cavity. Current is injected perpendicular to the junction to create a population inversion. Inversion only occurs once a certain threshold current density has been reached. For a given device geometry this can be related to a specific injection current. Below threshold the device behaves like a low intensity incoherent source, above threshold the output flux is a linear function of drive current as illustrated in Fig.2.2.

The emitting area of the laser is a narrow stripe, typically 2µm by 400µm for a 10W peak power laser. Different maximum power levels can be obtained by varying the major dimension of the emitting facet. It should be noted that increased output power is only obtained by a corresponding increase in source size, the brightness of the source remains unchanged. The output beam divergence angle is typically 10° parallel to the junction, and 5° perpendicular to the junction, thus fast optics (f/1.5) are required to collect all the laser output.
Fig. 2.1 Semiconductor laser diode geometry

Fig. 2.2 Typical laser diode drive current-optical power characteristic.
The emitting wavelength depends on the bandgap of the semiconducting material. For pulsed lasers gallium arsenide (GaAs) is used in a single heterojunction configuration giving an output wavelength of around 900nm. Typical optical flux rise times are in the sub-nanosecond region with peak powers up to 25W obtainable from a single diode. Repetition rates commensurate with a 0.1% duty cycle can be achieved. Unlike other laser sources injection lasers produce a very wide emission spectrum, of typically 5-10nm.

Increased output power, with no increase in input drive current, can be obtained from stacked arrays where several diode chips are mounted one above the other. This arrangement also has the advantage that a more symmetrically shaped source is produced. Power levels of up to one kilowatt (peak), with drive currents of 40A are commercially available.

Double heterojunction gallium aluminium arsenide (GaAlAs) laser diodes, which are used in the c.w. mode of operation, have a peak emission wavelength of about 820nm. The emission wavelength of these devices can be varied by changing the relative amounts of gallium and aluminium. Power levels are in the region of several milliwatts at bias currents of typically 100mA.

Recently, owing to interest in fibre optic transmission at 1.3 and 1.55μm, c.w. diodes based on indium gallium arsenide phosphide operating at these wavelengths have become available [Bergh 1980].
2.3 LASER MODULATION

Basically a laser beam can be modulated in two ways, by directly affecting the light generation within the laser itself (internal modulation) or alternatively by some modulating device outside the laser cavity (external modulation). Further, optical modulation methods can be broken down into four general categories:

1. Electro-optic
2. Acousto-optic
3. Direct modulation of laser power supply
4. Optical absorption

2.3.1 Electro-optic Modulation

Certain crystals when subjected to an electric field exhibit a change in birefringence. This is known as the Pockels effect. The Pockels effect gives rise to a phase retardation of a plane polarised wave as it propagates through the crystal. The degree of retardation is dependent on the modulating field and the geometry of the modulator.

Electro-optic modulators use this principle to vary the polarisation of a beam; to achieve intensity modulation a polariser is required at the output of the device, Fig.2.3. When the modulator is mounted inside the laser cavity frequency modulation can be achieved, since the effective optical path length can then be made to vary in proportion to the magnitude of the modulating signal.

Two other intracavity forms of modulation which employ
electro-optic devices are Q-switching and mode locking. When the gain of the laser cavity is reduced below that required for lasing a large population inversion can be built up. If then, by some suitable means, the gain is increased so as to enable laser action to occur the stored energy can be released in one short intense pulse. This technique is called Q-switching. In practice this is achieved by using an electro-optic modulator to 'spoil' the cavity Q by rotating the plane of polarisation away from the preferred orientation for laser action to occur. Mode locking occurs when the cavity gain is modulated at a rate equal to the longitudinal mode spacing. This results in very short, typically sub-nanosecond, pulses of high intensity being generated at repetition rates equal to the frequency separation of adjacent longitudinal modes \( (c/2l) \), where \( l \) is the cavity length.

Bandwidths of up to 2GHz [Izutsu 1978] have been reported with waveguide like structures using \( \text{LiNbO}_3 \) in the visible/near infrared region. At the \( \text{CO}_2 \) laser wavelength of 10.6\( \mu \)m devices with bandwidths of 1GHz have been achieved by utilizing either cadmium telluride or gallium arsenide as the active medium [Huang 1972].

2.3.2 Acousto-optic Modulation

The refractive index of some crystals can be changed by the application of mechanical strain. A convenient means of inducing strain is to propagate an ultrasonic wave through the crystal. When an optical beam crosses the
acoustic beam it is diffracted according to the local variations in refractive index. A zero order diffracted beam of optical frequency equal to that of the incident beam emerges undeflected whereas higher order beams suffer deflection and also a frequency shift of $\pm (n \cdot f_m)$, where $n$ is the diffraction order and $f_m$ the modulating source frequency.

When the optical beam is incident at the Bragg angle (which is typically less than $10^\circ$) then the light is scattered into only one diffraction order. The magnitude of the acoustic drive signal determines the relative magnitudes of the deflected and undeflected beams. Hence either output beam can be used depending on whether an in-phase or inverted amplitude modulated beam is required. A basic acousto-optic modulator is shown in Fig. 2.4.

2.3.3 Direct Modulation of Laser Power Supply

Direct variation of the laser power source can be used to amplitude modulate the laser output.

The optical output of a semiconductor diode laser can be modulated by direct variation of the pumping supply. Both c.w. and pulse modulation can be easily achieved [Paoli 1970].

Gas lasers can also be amplitude modulated via their power supply [Schiel 1963, Laakmann], although only at relatively low (less than 20KHz) frequencies.
Fig. 2.3 Electro-optic modulation

Fig. 2.4 Acousto-optic modulation
2.3.4 Modulation by Absorption

The optical transmission of some semiconductor crystals notably germanium and cadmium selenide [Williams 1960] can be varied by the application of a strong electric field. Generation of the high fields required is most easily achieved by reverse biasing a p-n junction [Racette].

De Cremoux [1969] describes a modulator for a CO₂ laser based on free-carrier absorption in germanium. The necessity to focus the laser beam to a spot size of less than 100μm restricts the laser power to 1W, owing to power dissipation limitations. Bandwidths into the megahertz region were attained with a modulation power of 1W.

2.4 LASER BEAM SCANNERS

The pointing requirements for laser radars are much more stringent than for conventional radars owing to the considerably narrower beamwidths which are employed. These narrow beamwidths generally preclude laser radars from operating in a target search mode. Rather, as outlined previously, their role is best suited to applications requiring high resolution coverage over a limited field of view. Scanning in this mode can be achieved with mechanical or solid state scanners, or a combination of the two.
2.4.1 Mechanical Scanners

The performance of optical scanners is usually expressed in terms of the number of resolvable spots or beam positions which can be achieved. The total angular extent can, of course, be expanded or contracted by use of suitable optics. The resolution of a mirror scanner can be expressed as [Fowler 1966]:

\[ N_r = \frac{\theta_{\text{max}} D}{e \lambda} \]  \hspace{1cm} (2.1)

where:

- \( \theta_{\text{max}} \) = max. scan angle
- D = scanner aperture
- e = 1 for a rectangular beam of uniform intensity
- 1.22 for a circular beam
- 1.27 for a Gaussian beam

For galvanometer scanners the mirror can be deflected to access randomly any of the resolution cells within its angular range, the resulting beam deviation being twice the angular excursion of the mirror. The time required to access a given deflection angle is [Zook 1974]:

\[ t_a = \frac{1}{2 f_0} \]  \hspace{1cm} (2.2)

where \( f_0 \) is the resonant frequency of the galvanometer.

The access time can only be increased at the expense
of resolution, since fast response requires small mirrors and hence lower resolution, with typically sub-millisecond access times being achieved with 1000 spot resolution. Zook [1974] gives a detailed account of the design philosophy of high speed galvanometer deflectors.

Plane mirror scanners may be used to produce a continuous scan but are unsuitable for high speed operation. For high speed line scanning the continuously rotating multifaceted drum mirror can be employed [Lloyd 1975]. Scanning speeds are limited by physical distortion of the mirror facets due to the large centrifugal forces, and ultimately by the bursting speed of the mirror. By varying the angle each mirror facet makes with the axis of the rotation an interlaced high speed scan can be produced.

Beam scanning can also be achieved by mounting the mirror on a piezoelectric actuator. In such devices a shear strain is produced when a voltage is applied to a piezoelectric crystal. This causes the mirror to tilt by an amount proportional to the drive signal amplitude. As the resulting tilt angle is inherently small multiple reflections between a number of mirror surfaces may be necessary to increase the scan angle.

Henshaw et al. [1980] describe a preliminary study of a discrete position beam switch for a 10.6μm laser radar. Their switch was made of two slightly non-parallel Fabry-Perot cavities in cascade separated by a small gap. Variation of the output cavity spacing, by a piezoelectric actuator, governed the number of 'bounces' between the
Fabry-Perots and hence the output beam direction. Simulation of a 16 by 16 array of spots with a separation of 2° indicated that access times approaching 0.1ms should be achievable.

2.4.2 Acousto-optic Scanners

The deflection angle for an acousto-optic scanner is proportional to the change in acoustic signal frequency and is given by [Korpel 1972]:

\[ \Delta \theta = \frac{\lambda \Delta f_m}{n \cdot v_a} \] ...........(2.3)

where

- \( f_m \) = acoustic wave frequency
- \( v_a \) = acoustic wave velocity
- \( n \) = refractive index

and the number of resolvable spots is equal to:

\[ N_r = \frac{\lambda \cdot \Delta f_m}{\theta_d \cdot v_a} \] ...........(2.4)

where

- \( \theta_d \) = diffraction limited beam divergence

and since \( \theta_d \) is approximately equal to \( \frac{\lambda}{nD} \)

\[ N_r = f_m \left[ \frac{D}{v_a} \right] \] ............(2.5)

The term in brackets is the time required for the acoustic
beam to transverse the optical aperture, and is the effective access time of the scanner. A second factor which limits the speed or resolution of acousto-optic deflectors is the attenuation of the acoustic wave as it propagates across the aperture. For most acousto-optic materials the drive power required to achieve a given angular deflection is proportional to the acoustic frequency [Pinnow 1970]. This, coupled with the reduced impedance of the device at high frequencies, which makes matching difficult, limits acousto-optic devices to a bandwidth of a few hundred megahertz.

A two dimensional scan may be achieved by placing two crossed acousto-optic deflectors in series. Driving each deflector with a suitable frequency modulated signal enables a variety of scan patterns to be generated.

King and Scholm [1978] have described a two dimensional acousto-optic deflector used to scan the receiver of a heterodyne 10.6μm laser radar. The scanner had a 12 by 12 spot (0.33 by 0.33mR) resolution with an access time of 1 microsecond. The overall scanner efficiency was 16-25%.

2.4.3 Electro-optic Scanners

Although the magnitude of the electro-optic effect is generally small and therefore large supply voltages are required in its application, extremely fast deflection rates are possible. The deflector commonly consists of a series of prisms, each successively inverted, and aligned so as to
form a bar [Lotspeich 1968]. When a voltage is applied across the bar the optical beam is progressively deflected. The access time of these devices, which is limited by the deflector capacitance and the available drive power, is given by [Zook 1974]:

\[ t_a = \frac{\eta \cdot C \cdot V_p^2}{P_a} \]  \hspace{1cm} (2.6)

where

- \( V_p \) = supply voltage
- \( P_a \) = electrical input power
- \( C \) = detector capacitance

Internal heating of the crystal can cause distortion of the beam, and thus limits the maximum drive power and hence the resolution and access time of the deflector.

Discrete position beam switching may be achieved by the use of a variable polariser and a birefringent detection element. By switching the polarisation of the incoming wave between two orthogonal states either the ordinary or extraordinary ray can be made to propagate through the birefringent crystal. Since the emerging beam direction is different for the two rays a 2 position switch can be constructed [Kulcke 1966]. Cascading \( n \) such cells enables \( 2^n \) possible beam positions to be addressed.
2.5 Detection

Optical detection is 'square-law' in nature, that is a photocurrent ($I_s$) is generated which is proportional to the square of the incident electric field. In a photodetector the photocurrent is related to the average incident optical power, ($P_{sd}$), by :-

$$\frac{I_s}{P_{sd}} = \frac{\eta \cdot q}{h \cdot v} \quad \ldots \ldots (2.7)$$

where

- $\eta$ = quantum efficiency
- $h$ = Planck's constant
- $q$ = electronic charge
- $v$ = optical frequency

This ratio is called the detector responsivity and is a commonly quoted detector parameter.

Detection can be performed either incoherently (direct detection) or coherently (heterodyne detection) as for radio frequency reception. However, unlike the radio frequency case in which heterodyne detection results in a significant improvement in sensitivity, in the optical region where quantum effects may dominate, the improvement is often less pronounced.
2.5.1.1 Direct Detection

Direct detection receivers focus the incoming optical signal, made up of the wanted signal together with background radiation, directly onto the photodetector, Fig.2.5. Since the photodetector responds only to the incident energy, phase and spectral information are not preserved in the detection process. The photodetector will respond equally well to both signal and background photons within its spectral response. To achieve rejection of the background component, optical pre-filtering is required.

Several noise mechanisms are present in the detection process. In the absence of any other noise sources the limiting factor on direct detection receiver sensitivity is signal induced shot noise. This is a fundamental limitation due to fluctuations in the photon arrival rate. Shot noise will also be generated by the background radiation not rejected by the optical filter, and also from leakage currents within the detector itself. Also the output resistance of the detector will generate thermal noise, which for detectors without pre-detection gain, is commonly the dominant noise source.

The signal to noise ratio at the output of a photodetector can be expressed by :-

\[
SNR = \frac{P_{sd} R_e G}{(2 q B R_e (P_{sd} + P_{bd}) G(2+x) + kTB/R_p)^{1/2}} \quad \ldots (2.8)
\]
where

\[ P_{sd} = \text{detected signal power} \]
\[ P_{bd} = \text{detected background power} \]
\[ G = \text{pre-detection gain} \]
\[ x = \text{excess noise factor} \]
\[ R_p = \text{effective photodiode load resistance} \]
\[ R_e = \text{photodiode unity gain responsivity} \]
\[ B = \text{electrical bandwidth} \]

It follows from eq.(2.7) and (2.8) that the theoretical minimum detectable power \( P_{sd_{\text{min}}} \) for a direct detection receiver is given by:

\[ P_{sd_{\text{min}}} = \frac{2qB}{R_e} \quad ...........(2.9) \]

\[ = \frac{2hvB}{\eta} \quad ...........(2.10) \]

The improvement in receiver sensitivity which can be achieved by having pre-detection gain (as can be obtained from photomultipliers and avalanche photodiodes) can be clearly seen from eq.(2.8). For unity and low gains the thermal noise term is dominant. As the gain is increased so the SNR improves until the shot noise term becomes comparable with the thermally generated noise. Beyond a certain limit any further increase in gain will result in a decrease in SNR since the gain process itself generates additional noise.
COLLECTING LENS

INCOMING RADIATION
(signal + background)

PHOTODETECTOR

OPTICAL FILTER

Fig. 2.5 Basic direct detection receiver

BEAMSPLITTER

PHOTODETECTOR

INCOMING RADIATION
(signal + background)

LOCAL OSCILLATOR

Fig. 2.6 Basic heterodyne receiver
The optimum value of gain can be found by differentiation of equation (2.8), :-

\[ G_{\text{opt}} = \left[ \frac{kT}{xqR_pR_e(P_{sd} + P_{bd})} \right]^{\frac{1}{2+x}} \ldots (2.11) \]

Owing to their simplicity and good sensitivity direct detection systems have found widespread use in laser ranging systems. However, in some applications, for example where accurate target velocity information is required, a coherent detection scheme can be used to good effect.

2.5.1.2 Heterodyne Detection

It has only been since the advent of the laser that heterodyne (or photomixing) has become possible in the optical region. The basic principle of photomixing is shown in Fig.2.6.

The incoming optical signal is mixed with a local oscillator beam (which is derived from the same source as the signal itself) on the surface of a photodetector. For efficient photomixing to occur the wavefronts of the two beams must be parallel across the photosensitive area and should also be of like polarisation [Ross 1966]. At the output of the photodetector a component at the optical difference frequency will be produced. The bandwidth of the detector and its associated circuitry must, of course, be sufficient to accommodate the beat frequency.
It can easily be shown [Oliver 1961] that the limiting SNR for a heterodyne receiver is given by:

\[ \text{SNR} = 1 = \frac{\eta \cdot P_{sd}}{h \nu B} \]  

where \( P_{sd} \) is the signal power, \( h \nu B \) is the noise equivalent power, \( \eta \) is the system efficiency, and \( \nu \) is the signal frequency. This results in:

\[ P_{sd\text{min}} = \frac{h \nu B}{\eta} \]

which is only a 3dB improvement over the direct detection receiver operating under the ideal conditions of no background radiation.

It is the high power local oscillator signal which provides the large conversion gain which effectively swamps all noise sources other than its own shot noise. Extremely high rejection of background radiation is thus achieved since the effective optical bandwidth is equal to the post detection intermediate frequency bandwidth. By comparison direct detection receivers can only reject background radiation by means of optical interference filters whose bandwidth is normally much larger than the post detection bandwidth, being of the order of many 100's of gigahertz.

The large Doppler shifts which can occur from moving targets at optical frequencies can be detected with a heterodyne receiver and hence target radial velocity can be estimated. The magnitude of the Doppler shift \( f_d \) is given
by:

\[ f_d = \frac{2v_v t}{c} \quad \ldots \ldots \ldots (2.14) \]

where \( v_t \) = target radial velocity (m/s)

At a wavelength of 1\( \mu \)m Doppler shifts of 2MHz per m/s of radial velocity will occur. Although the velocity resolution of optical heterodyne receivers is excellent difficulties may be experienced with fast moving targets. For example, an oncoming aircraft travelling at 1000km/hr will produce a Doppler shift of some 26MHz at the carbon dioxide laser wavelength.

The advantages of heterodyne detection become more pronounced at the longer infrared wavelengths, e.g. in the 8-14\( \mu \)m atmospheric window. Firstly the receiver alignment is less critical (compared to the shorter wavelengths) and secondly good increases in sensitivity can be achieved over direct detection receivers [Teich 1968]. The comparative sensitivity increase occurs since signal shot noise is rarely the dominant noise source at the longer wavelengths. A 10.6\( \mu \)m heterodyne laser radar equipment described by Brandewie [1972] achieved a SNR within a factor of four of the theoretical quantum limit. A third advantage is that atmospheric scintillation and attenuation tend to be lower than in the visible/near infrared region.

Target speckle effects [Dainty 1975] should also be considered if a heterodyne receiving system is used. Most
targets can be considered as diffuse scatterers, that is the reflected signal is composed of contributions from a large number of scattering sites. In such cases the intensity of the reflected signal across the receiver plane will appear as a non-uniform random pattern. The intensity follows a Gaussian distribution with the average size of the speckle 'blobs' being approximately $\lambda R/D$ where $R$ is the targets range and $D$ is the diameter of the illuminated area. Target speckle places an upper limit on the size of the receiving aperture which can be usefully used. Since a heterodyne receiver requires a constant phase signal for efficient detection, and as the phase of different speckle blobs are distributed over the range $-\pi$ to $+\pi$ collecting more than one blob is not beneficial. If the target is moving then temporal variations will occur in the speckle pattern. These can be characterised by attributing a coherence time to the target. This is an important consideration for systems using, for example, pulse compression techniques since it places a limit on the length of the transmitted waveform which can be used.

2.5.2 Optical and Infrared Detectors

Optical and infrared detectors can be classified into two general groups - those responding to thermal effects and those responding directly to incident photons.

Before discussing the different detectors available it is necessary briefly to outline the parameters commonly used to describe detector performance.
The detector will introduce noise owing to device imperfections and so a means of assessing the sensitivity of a detector is required. This is commonly done in terms of the detector's noise equivalent power (NEP), which is defined as the optical input power incident on the photosensitive surface necessary to produce a signal-to-noise ratio of unity at the detector output. The reciprocal of the NEP is defined as the detectivity (D), a quantity which increases with improving detector performance. A normalised specific detectivity, \( D^* \) (pronounced D star) was introduced by Jones[1959] as a more valid parameter for comparing detectors of different areas and measurement bandwidths. The units of \( D^* \) are \( \text{cm}\sqrt{\text{Hz}}/\text{W} \).

### 2.5.2.1 Thermal Detectors

Because thermal detectors respond to the heating effect produced by the incident radiation they are generally slow (typically milliseconds) and are also comparatively insensitive. However, this type of detector has a wide spectral response. The low sensitivity and slow response time make thermal detectors unsuitable for most laser radar applications, although one that utilises the pyroelectric effect, has several desirable features.

Pyroelectric detectors respond to the rate of change of radiance by inducing an electric dipole moment in an insulating material such as Triglycine Sulphate (TGS). Their low frequency sensitivity is an order of magnitude or so less than that of photon detectors although response
times in the subnanosecond region can be achieved at reduced sensitivity. The ability to operate at room temperature, even in the 8-14μm band, has resulted in the device being used as the mixing element in heterodyne receivers [Abrams 1969].

2.5.2.2 Photon Detectors

Two types of photon detector are of interest here, photoemissive detectors and solid state semiconductor devices. The most common type of photoemissive device is the photomultiplier tube (PMT). These detectors consist of a photosensitive cathode and a series of dynodes, which provide internal current amplification, and an anode to collect the photocurrent. For operation in the visible region photomultipliers provide the most sensitive form of direct detection. However, in all but the most critical applications the solid state avalanche photodiode (APD) is preferred owing to its lower cost, simpler power supply requirements and small rugged construction. Above 800nm the quantum efficiency of even the longest cut-off wavelength photomultiplier is so low that the APD becomes an even more attractive choice.

The APD is a pn junction device reverse biased to the point of breakdown. Carrier multiplication occurs owing to impact ionization, with gains of several hundred being achieved at bias voltages of a few hundred volts.

For detection further into the infrared, to about 1.7μm, germanium [Ando 1978] and more recently InGaAsP
[Yeats 1979] based detectors are normally used. Both types are available for use in the avalanche mode of operation.

Above 2\textmu m the thermal energy of the electrons within the detector material at room temperature becomes comparable with the energy of the incident photons. Therefore, for sensitive direct detection some means of cooling the detector is required. Commonly used detector cooling techniques are outlined in the following section.

Two ternary alloy detectors, cadmium mercury telluride (CMT) and lead tin telluride (LTT) are used for high speed detection at the longer infrared wavelengths out to the limit of the 8-14\textmu m atmospheric window. The CMT detector is now replacing the LTT device in most applications. The peak response of the CMT detector can be tailored to any specific wavelength in the 2-14\textmu m region by adjusting the HgTe to CdTe ratio of the material. Detectivities of $10^{11}\text{cm}/\sqrt{\text{Hz/W}}$ in the 3-5\textmu m region (detector temperature 195 K) and $2.10^{10}\text{cm}/\sqrt{\text{Hz/W}}$ at 8-14\textmu m (77 K) with response times of less than 10ns are typical. In addition to single element detectors CMT arrays having 100 elements are available for use primarily in thermal imaging applications. Considerable research effort is currently being devoted to the development of two dimensional high resolution 'staring arrays' which require no mechanical scanning [Charlton 1982].
2.5.2.3 Detector Cooling

In order to obtain optimum performance from the detector at wavelengths longer than about 3µm it is necessary to suppress thermally excited charge carriers by operating the detector at reduced temperature.

Operating temperatures suitable for detectors operating in the 3-5µm atmospheric window can be achieved using thermo-electric heat pumps [Davis 1981]. Utilizing the Peltier Effect detector cooling down to 195 K can be obtained with 4 stage coolers for electrical input powers of a few watts. The minimum operating temperature obtainable with thermo-electric coolers is limited to about 170 K.

At longer wavelengths, for example in the 8-14µm band, detector operating temperatures of 77 K are normally required. Direct cooling of the detector with liquid nitrogen is a simple and effective means of cooling, however it is only really practical in laboratory type environments since readily available supplies of liquid nitrogen are required. For operation in more practical situations Joule Thompson and various types of cooling engine (the most common type is the Stirling engine) powered by compressed gas can be used [Stephens 1968]. When driven from a compressor unit, as opposed to a gas bottle, continuous operation of several hundred hours can be achieved.
2.6 ATMOSPHERIC EFFECTS

2.6.1 Attenuation in Clear Weather

For a laser radar system the transmittance \( T \), through the atmosphere to a target at a range of \( R \) kilometres, is related to the extinction coefficient \( \sigma \) (per km) by the expression \( T = \exp(-2\sigma R) \). In general attenuation of optical radiation is caused both by scattering and by absorption. The extinction coefficient can thus be split into two components;-

\[
\sigma = \sigma_{\text{scat}} + \sigma_{\text{abs}} \quad \ldots \ldots \quad (2.15)
\]

where

- \( \sigma_{\text{scat}} \) is the scattering coefficient
- \( \sigma_{\text{abs}} \) is the absorption coefficient

In the visible and infrared regions of the spectrum atmospheric attenuation is a rapidly varying function of wavelength having several strong absorption bands caused principally by water vapour and carbon dioxide molecules [Kruse 1962]. There are however, three regions where reasonably efficient propagation is possible, - the visible and near infrared (0.4-1.2\( \mu \)m), and the two infrared windows at 3-5\( \mu \)m and 8-14\( \mu \)m. A typical clear weather atmospheric propagation curve is shown in Fig.2.7. Also shown is a magnified view of the region around 10\( \mu \)m indicating that considerable fine detail is in fact present.
Theoretical predictions of molecular absorption at any wavelength of interest can be made using one of several computer programs written for the purpose, such as the AFCL LASER program [McClatchey 1978]. Attenuation caused by molecular scattering can usually be neglected in comparison to molecular absorption.

Scattering and absorption are also caused by aerosols and particulate matter present in the atmosphere. The scattering is generally classified as being either Rayleigh or Mie. Rayleigh scattering occurs when the wavelength is considerably greater than the dimensions of the scattering particles. Under these conditions scattering exhibits an inverse fourth power dependence on wavelength, so that for a given particle size attenuation increases rapidly as the wavelength is reduced. Mie scattering becomes the dominant mechanism when the particle size is larger than the wavelength. In this region the scattering is independent of the wavelength.

Over extended path lengths the aerosol composition and concentration can vary considerably making theoretical predictions difficult, if not impossible. Consequently the attenuation coefficient is often predicted for a given operating site by measurement of the visual range, which is defined to be the range at which an object can just be perceived against the background with the unaided, adapted human eye. This represents a contrast difference between object and background of approximately 2%.

The scattering coefficient can be related to the
Fig. 2.7 Clear weather propagation characteristic
visual range, \( V \) (in kilometres) at a given wavelength (in microns) by the expression [Kruse 1962] :-

\[
\sigma_{\text{scat}} = \left( \frac{3.9}{V} \right) \left( \frac{0.55}{\lambda} \right)^p 
\]

\( \ldots \ldots (2.16) \)

where \( p = 0.585V^{1/3} \) for \( V < 6 \)

2.6.2 Attenuation by Precipitation

Attenuation caused by rain, snow, fog, etc. can result in a significant, if not the total, degradation of the capabilities of a laser radar and will generally provide the 'worst case' operating conditions. Thus no optical based radar system operating through the atmosphere can be said to provide true 'all weather' operation.

In addition to the loss of the wanted signal by attenuation considerable scattering of the transmitted laser beam back into the receiver can be expected whenever scattering is the dominant attenuation mechanism. The degree to which this unwanted atmospheric backscattering will affect a laser radars performance depends on a number of factors. Most susceptible are systems employing c.w. modulation schemes since the receiver cannot be 'gated' to exclude the backscatter return as can be done with pulsed systems.

Van de Hulst [1957] has derived expressions which relate the scattering and absorption cross-sections of water
droplets to the droplets radius, the wavelength, and the complex refractive index. Fig. 2.8 shows graphically how the cross-sections vary as a function of the droplet radius for wavelengths of 0.63, 3.5 and 10.6μm.

The attenuation coefficients can be related to the attenuation cross-sections:-

\[ \sigma = \pi r^2 \int n(r) \cdot Q(r, \lambda) \cdot dr \]  \hspace{1cm} (2.17)

where
- \( Q \) = scattering or absorption cross-section
- \( r \) = spherical drop radius
- \( n(r) \) = drop size distribution

The relative contributions from absorption and scattering can be estimated in the idealized case of uniform droplet size by setting \( n(r) \) equal to

\[ \frac{w}{\frac{4}{3} \pi r^3} \cdot \delta(r) \]

where
- \( w \) = liquid water density
- \( \delta(r) \) = delta function

and substituting into eq.(2.16). The attenuation coefficient then becomes :-

\[ \sigma = 3.25 \frac{Q}{r} \frac{\text{dB}}{\text{km}} \frac{\text{mg}}{\text{m}^3} \]  \hspace{1cm} (2.18)
Fig. 2.8 Extinction and absorption cross-sections as a function of water droplet size (after Chu [1968])
It is apparent from eq.(2.18) why fog produces such strong attenuation in the optical region. Although the water content of a typical fog is a factor of 10 or so less than in say a rain shower the droplet size is about a factor of 1000 less, resulting in significantly higher attenuation.

Fig 2.9 shows the total extinction and absorption coefficients plotted as a function of water droplet size. The peak of each extinction curve occurs when the particle size is approximately equal to the wavelength. The 'Q' of a curve depends on the relative magnitudes of the scattering and absorption coefficients. The curve for 0.63μm shows a very pronounced peak since scattering is the dominant attenuation mechanism.

As can be seen from Fig. 2.9 for water droplet sizes below 10μm (corresponding to fog droplet sizes), the CO₂ laser wavelength of 10.6μm gives the lower attenuation. For water droplet sizes above 10μm the attenuation becomes essentially 'white' for the wavelengths of interest here. In practice a fog or rain shower is composed of droplets of various sizes so that the particle size distribution needs to be known in order to evaluate the mean extinction coefficient.

When scattering is the principal attenuation mechanism a correction should be applied to eq.(2.16) to allow for forward scattering which has the effect of reducing the attenuation coefficient [Chu 1968].
Fig. 2.9 Extinction and absorption coefficients as a function of water droplet size (after Chu [1968])
2.6.3 Atmospheric Dispersion and Depolarisation

In the clear atmosphere the effects of atmospheric dispersion and depolarisation are generally small. Brookner [1969] has calculated that in clear weather and in the absence of turbulence pulse distortion due to frequency dependent refractive index variations will not become significant until the bandwidth is of the order of 100Ghz.

When a collimated laser beam propagates through a region of low atmospheric visibility such as fog several other effects occur in addition to a reduction in beam intensity. Multiple scattering of the laser light results in a decollimation of the beam and a corresponding increase in its spatial extent. If, for example, a pulsed radar is used the multiple scattering of the beam can also broaden the transmitted pulse significantly and this will degrade the range resolution. In addition if the various scatterers are in relative motion then an initially monochromatic beam will emerge with a superimposed frequency spectrum. The magnitude of this Doppler spectrum is, however, generally small. An extensive overview of wave propagation in scattering media is given by Ishimaru [1977].

2.6.4 Turbulence

Turbulence is caused by the constant motion and mixing of local air pockets (eddies) within the atmosphere. Warmer air pockets, having lower density than the cooler eddies exhibit a lower refractive index. Although the refractive
index changes are small, being typically a few parts per million, they may modify the propagation characteristics significantly. The variations in refractive index are usually characterised by the 'refractive index structure parameter' $Cn^2$ [Lawrence 1970].

When propagating through eddies much smaller than the beam diameter an optical beam of initially uniform power density will be 'broken up' so that the intensity distribution across the beam becomes a random, time-varying pattern. This is termed scintillation. The average size of the individual elements (often referred to as 'blobs') within the beam is approximated by $(\lambda R)^{1/6}$ where $R$ is the path length. As the eddies are in constant motion amplitude fluctuations may occur as the blob pattern moves across the receiver aperture. The temporal variations of the beam intensity are determined mainly by the cross wind speed, with frequencies up to 250Hz being recorded [Brookner 1970].

When the predominant eddy size is larger than the beam diameter, beam wander (sometimes referred to as twinkling or spot dancing) can occur. If the transverse beam wander at the target should become greater than the product of the receiver field-of-view and the target range then the receiver would no longer detect any scattered power. Beam deflections are however generally small, being in the range 1-100 microradians, resulting in a lateral movement of, for example, a few centimetres at a range of 1km [Davis 1966].

For heterodyne detection the effects of turbulence limit the useful collecting aperture which may be employed.
Fried [1968] has introduced a parameter, \( r_0 \), which characterises turbulence induced wavefront distortion. For collecting apertures much smaller than \( r_0 \) the SNR of the detection process improves, as would be expected for a diffraction limited aperture, in proportion to the square of the diameter. However, for collecting apertures much larger than \( r_0 \) the SNR can never be greater than about 3dB above that which would be obtained from a receiver diameter equal to \( r_0 \). It is worth noting at this point that target speckle effects must also be considered when selecting the receiver aperture size for a heterodyne receiver.

2.6.5 High Power Propagation

In the preceding sections an understanding implicit in the discussion of propagation effects has been that the propagating laser beam in no way affects the propagation medium. For very high power levels, however, it can be expected that the medium will be, to some extent, altered and hence the propagation characteristics modified. When this occurs in the clear atmosphere it is termed thermal blooming [Walsh 1978]. Partial absorption of the laser beam in the medium gives rise to localised heating and a corresponding pressure increase. The resulting decrease in air density produces changes in local refractive index which tend to make the beam spread out or 'bloom'.

The threshold level for thermal blooming to occur in typical atmospheric conditions has been calculated by Walsh [1978] to be of the order of 1kW (continuous wave) for a CO\(_2\)
laser beam. Fortunately this is 1 to 2 orders of magnitude greater than power levels which would be used for most laser radar applications.

High power pulsed laser transmission through fog and clouds has also been investigated by several workers [Kafkas 1973, Dunphy 1977, Sutton 1978]. At a wavelength of 10.6μm Sutton shows that a laser fluence of approximately 0.4J/sq.cm. can clear a 1km path length in hazy conditions, whereas 40J/sq.cm. is required for a thick fog. Again these power levels are significantly higher than those which would be used in a laser radar system.
CHAPTER III

SHORT DURATION PULSING OF LASER DIODES

3.1 INTRODUCTION

The pulsed semiconductor diode laser has several attributes which make it ideal for many short range active imaging and ranging applications. For instance, its small physical size, low cost, and relatively simple drive requirements enable a very compact transmitter assembly to be produced. A natural consequence of the relatively short operational range of such systems is that enhanced ranging accuracy and resolution are often required. This in turn necessitates the generation of optical pulses of typically only a few nanoseconds duration.

It was observed from preliminary experiments that when operating pulsed semiconductor lasers in this regime laser turn-on effects can modify the device's performance. Most significantly, the laser's threshold current increases with reducing drive current pulsewidth. Output power and pulse shape are also strongly dependent on the drive current waveform especially near the threshold current.

Most of the literature published on the performance of semiconductor laser diodes has been principally concerned with c.w. double heterostructure devices [Chown 1973]. As little relevent work has been published on the performance of single heterostructure lasers when pumped with short
duration current pulses this present study was initiated.

Knowledge of the laser output peak power and temporal response are obvious prerequisites if the system performance is to be accurately predicted. A means of relating the drive current parameters to the laser output is required. This is the topic of the present chapter. Both experimental and theoretical studies have been undertaken. An automated measurement system capable of recording both the driving current and optical waveforms was constructed. During the course of this experimental work it became apparent that temporal variations were present across the beam. A detailed examination of this phenomenon is outside the scope of this present work; however a brief insight into the effects observed are given in Appendix 3.1.

A computer simulation, written in FORTRAN77 and implemented on the University's central computers, has been developed which enables a laser's performance to be predicted under a variety of operating conditions. Comparison of the predicted and measured responses shows good agreement.

3.2 THE EXPERIMENTAL SYSTEM

A computer controlled data acquisition system for recording both current into, and optical pulses generated by, the laser under test was set up; it is shown in Fig.3.1. A desktop microcomputer (Hewlett Packard HP85) controls the operation of the system via an IEEE-488 instrumentation data bus. A dual beam sampling oscilloscope
(Tektronix 7704 with S14 sampling plug-in) is used to sample both current and optical waveforms. The computer steps the time base of the oscilloscope, via the digital to analogue converter through each waveform in turn. At each step the amplitude of the waveform is recorded by a 7 digit digital voltmeter (Solatron no. 7060). The propagation delays along the cables CA1 and CA2 were matched to better than 0.5ns so that accurate relative time measurements could be made between the current and optical waveforms. Each waveform is stored on cassette tape for later analysis.

![Fig. 3.1 Laser current pulse and optical pulse measurement system](image)
The photodetector is a silicon avalanche photodiode with an active diameter of 0.2mm. The bias voltage (approximately 160 volts) is applied via a biased tee coupler from a stabilized high voltage supply. The combined risetime of the photodetector and sampling oscilloscope was estimated to be approximately 400ps. A collecting lens could be placed in front of the photodetector so that most of the laser output would be sampled or alternatively without the lens the detector alone could probe a small part of the laser output.

To obtain the absolute value of the peak optical output the average optical power was measured, using a large area slow response-time photodetector which ensured that all the optical output was collected. From a knowledge of the optical pulse shape and the pulse repetition rate the instantaneous optical power was then determined.

Three commercial laser diode pulsers, Fig.3.2, were used in the experiments. The characteristics of the pulsers are listed in Table[3.1].

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model No.</th>
<th>Pulsewidth (ns)</th>
<th>Max. Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Technology</td>
<td>IL40C</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>Avtech</td>
<td>AVO-P</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>Avtech</td>
<td>AVO-3A-P</td>
<td>3</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 3.1 Laser Pulsers
a) Power Technology model no. IL30C10-P8 pulser

b) Avtech model no. AVO-3A-P pulser

Fig. 3.2 Commercial laser diode current pulsers
For all three pulsers the output current could be varied although the pulsewidth was fixed. The Power Technology pulser was equipped with a current monitoring facility whereas the Avtech pulsers required a small-value resistor in series with the laser to act as a current sensing device. Physically this resistance was obtained by the parallel connection (to reduce lead and package inductance) of three 10\,\text{ohm} resistors. A coaxial connection across the composite resistance was made directly to the sampling oscilloscope. Owing to the low impedance of the current sensing resistance this connection acts essentially as a voltage probe.

Four single heterostructure pulsed laser diodes, with threshold currents (for a 200\,\text{ns} pulse duration) ranging from 5-22\,\text{A} have been examined. The details of the lasers are given in Table [3.2].

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Laser Type</th>
<th>Threshold Current (A)</th>
<th>Max. Rated Power Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITT</td>
<td>LA1-02</td>
<td>5.5 ,\text{A}</td>
<td>-</td>
</tr>
<tr>
<td>RCA</td>
<td>SG2007</td>
<td>13.5</td>
<td>10W @ 40A</td>
</tr>
<tr>
<td>LDL</td>
<td>LD65</td>
<td>13</td>
<td>10W @ 40A</td>
</tr>
<tr>
<td>LDL</td>
<td>LD67</td>
<td>22</td>
<td>18W @ 60A</td>
</tr>
</tbody>
</table>

Table 3.2 Laser Diode Characteristics.

Each laser was operated in conjunction with each pulser at various peak currents. The results obtained are
presented in section 3.4 where they are compared with theoretically predicted results.

In addition to the results obtained with the measurement system described above a series of measurements was carried out with an electro-optic streak camera. The time resolution of the streak camera was in the range 10-100ps so that little temporal smoothing of the laser output occurred on the higher time resolution ranges [Hull 1980]. As a streak camera produces a two-dimensional intensity modulated output of time versus spatial position a linear array CCD was used to record the temporal output from the camera faceplate. These results are also presented in section 3.4.

3.3 THEORETICAL RESULTS

3.3.1 The Rate Equations

The time behaviour of the photon density in a semiconductor laser is related to the excess carrier concentration and hence to the pumping current density by means of the coupled rate equations [Adams 1973, Tucker 1981, Thompson 1980]:-

\[
\frac{dN_e}{dt} = \frac{J}{q.d} - \frac{N_e}{T_s} - A(N_e - N_{eb})N_p \quad \ldots \ldots (3.1)
\]

\[
\frac{dN_p}{dt} = A(N_e - N_{eb})N_p - \frac{N_p}{T_p} + \frac{\beta N_e}{T_s} \quad \ldots \ldots (3.2)
\]
where

\[ N_e = \text{carrier concentration in the active region} \]
\[ J = \text{drive current density} \]
\[ d = \text{recombination width} \]
\[ T_s = \text{spontaneous relaxation time of electrons} \]
\[ A = \text{proportionality constant} \]
\[ N_{eb} = \text{background electron density required for positive gain} \]
\[ N_p = \text{photon density} \]
\[ T_p = \text{average photon lifetime} \]
\[ \beta = \text{probability of a spontaneously emitted electron radiatively combining into the lasing mode} \]
\[ q = \text{electronic charge} \]

When using these equations the following simplifying assumptions were made:

1. The gain coefficient was assumed to be linearly related to the free electron carrier density above a background level of \( N_{eb} \). An approximate value for \( N_{eb} \) can be calculated from the curves given by Kressel [1977]. For undoped GaAs a current density of approximately 4000 A/cm\(^2\)/\( \mu \)m is required to achieve a positive gain coefficient at 300 K.

Hence from eq.(3.1) we have, since \( N_p = 0 \) below
threshold

\[ N_{eb} = \frac{J}{q\cdot d} \cdot T_s \quad \ldots \ldots (3.3) \]

For instance, for \( T_s = 5\text{ns} \) (see below) and \( d = 2\mu\text{m} \) (the cavity height of the 5.5A threshold ITT laser diode used in the measurements) we obtain :-

\[ N_{eb} = 6 \cdot 10^{17} \text{ cm}^{-3} \quad \ldots \ldots (3.4) \]

2 .... only a single mode is presumed to be lasing. Experiments show that this is clearly not the case in a practical laser diode. However, the assumption does enable an approximate prediction of the laser output to be obtained.

3 .... the electron and photon time constants are assumed to be independent of carrier concentration.

A measure of the electron lifetime can be obtained by observing the decay time of the optical output when the device is excited with a low-level (i.e. less than threshold) current impulse. Alternatively the diode may be modulated with a low-level c.w. signal and the -3dB point determined. The electron lifetime is then :-

\[ T_s = \frac{1}{w_c} \quad \ldots \ldots (3.5) \]

where \( w_c \) is the measured cut-off angular frequency
Using this second approach a value of approximately 5ns was obtained for the carrier lifetime of the same laser.

The photon lifetime is defined as the average time a photon remains within the optical cavity before it is either emitted through the end facets or is lost through absorption.

The photon lifetime can be expressed as [Kressel 1977]:

\[ T_p = \left( \frac{c}{n} \cdot (\bar{\alpha} + L^{-1} \cdot \ln R^{-1}) \right)^{-1} \quad \ldots \ldots \quad (3.6) \]

where \( L = \) cavity length (cm) (0.04cm for 5.5A laser)
\( R = \) mirror reflectivity (assumed to be the same for both mirrors at 0.32)
\( n = \) refractive index, assumed to be 3.5 for GaAs
\( \bar{\alpha} = \) absorption coefficient (typically 10 cm\(^{-1}\))

substituting values we obtain :

\[ T_p = 3 \text{ ps} \quad \ldots \ldots \quad (3.7) \]

Using the rate equations under the above assumptions a computer program was developed which enables the laser's temporal response to be predicted under a wide variety of operating conditions. The program enables the user to vary all the parameters in eq(3.1),(3.2) and also to specify the characteristics of the drive current waveform. A full
description of the program together with a listing is given in Appendix 3.2.

3.3.2 Prediction of Laser Performance

All the predicted responses given in this section have been calculated for a laser threshold current of 5.5A (the threshold of the ITT laser used in the measurements).

3.3.2.1 Laser Temporal Response

The discussion here will be limited to half-sine current pulse waveforms so that direct comparisons can be made with the experimental results. Three predicted laser output waveforms are shown in Fig.3.3 for 4ns, 25A; 16ns, 35A; and 40ns, 35A half-sine drive current pulses.

As can be seen from Fig.3.3 after a delay which depends on the peak current (see section 3.3.2.4) a very fast rising optical pulse occurs. A damped high frequency oscillation then occurs which dies away within a period approximately equal to the spontaneous relaxation time. The frequency of this oscillation is given by [Kressel 1977] :-

\[
f = \frac{1}{2\pi} \left( \frac{1}{T_s T_p} \cdot \left[ \frac{I_p}{I_t} - 1 \right] \right)^{\frac{1}{2}} \quad \ldots \ldots \quad (3.8)
\]

where

\[I_p = \text{peak drive current (A)}\]
\[I_t = \text{'long pulse' threshold current (A)}\]

These high frequency oscillations are not normally visible when the laser output is observed with a photodiode based
Fig. 3.3(a) Predicted laser output for half-sine current pulse. Drive current 25A, 4ns base width duration.

Fig. 3.3(b) Predicted laser output for half-sine current pulse. Drive current 35A, 16ns base width duration.
Fig. 3.3(c) Predicted laser output for half-sine current pulse. Drive current 35A, 40ns basewidth duration.

receiver. Firstly, in general the bandwidth of the receiver will not be sufficient to reproduce the detected signal faithfully. Secondly, shot-to-shot variations in the laser output tend to mask the presence of the oscillations.

Damping is provided by the spontaneous emission term . Values of $\beta$ used by other workers [Kressel 1977, Goodwin 1982, Boers 1975] are in the range $10^{-5}$ to $10^{-2}$. A value of 0.002 for $\beta$ was chosen for this study since it gave the best correlation between the predicted responses and those obtained with a high speed streak camera recording of the laser output.

Once the laser turn-on effects have diminished the laser output follows the shape of the modulating current waveform, Fig.3.3(c).
3.3.2.2 Drive Current-Optical Power Transfer Characteristic

Drive current versus optical power transfer characteristics have been calculated for both rectangular and half-sine current pulses of various pulsewidths. The results were obtained by running the laser simulation program and automatically varying the peak current in 1A steps between 0 and 40A for each pulse duration. The rate equations were solved for each peak current and pulsewidth and the corresponding peak power and pulse energy obtained.

The predicted variation of peak optical power versus applied current for different pulse durations is shown in Figs.3.4,3.5 for rectangular and half-sine pulses respectively. It is evident in both cases that the peak current required to attain stimulated emission increases as the pulsewidth is reduced. For a rectangular current pulse of duration $t_{pw}$ it follows from eq(3.1) that the required current to achieve stimulated emission is given by:

$$I_{teff} = \frac{I_t}{1 - \exp(-t_{pw}/T_s)} \quad \ldots \quad (3.9)$$

where

$I_{teff} =$ effective threshold current for a drive current of pulsewidth $t_{pw}$

Stimulated emission occurs when the carrier density within the cavity reaches the threshold level, $N_{eth}$.

This corresponds to a charge level of :-
Fig. 3.4 Transfer characteristic for rectangular drive pulse.

Fig. 3.5 Transfer characteristic for half-sine drive pulse.
to achieve lasing.

From eq(3.9) it is apparent that for pulse durations much shorter than the spontaneous relaxation time the injected charge level at threshold is \((I_t . T_s)\). For pulse durations comparable with \(T_s\) the injected charge must be increased to:

\[
\frac{I_t}{(1 - \exp(-t_{pw}/T_s))} . t_{pw} \quad \ldots \ldots \quad (3.11)
\]

For a half-sine drive current pulse the effective threshold current is increased compared to a rectangular pulse of the same duration. For pulse durations approximately equal to or less than the spontaneous relaxation time the threshold increases by a factor of \(\pi/2\) (the ratio of the areas of a rectangular and half-sine pulse).

The transfer characteristic for the rectangular drive current pulse is composed of two parts. At threshold the laser turn-on delay is approximately equal to the drive current pulse duration. For peak currents just in excess of threshold the current pulse terminates before the first oscillation of the laser output is completed. Hence the optical output does not reach its maximum (long pulse) value. However, when the peak current is increased only
slightly further, the time delay reduces and the laser output rises rapidly and soon attains its long-pulse value. Beyond this point, which occurs at approximately constant charge, the laser output becomes independent of pulse duration.

3.3.2.3 Effect of Biasing the Laser

The increase in threshold current required when short duration current pulses are used to pump the laser causes a significant reduction in output power. Increasing the peak drive current to compensate for this is not an attractive proposition since the rate of change of current soon becomes excessive. However, an alternative approach can be adopted which enables the threshold electron density to be reached without 'wasting' the pumping current. A current of amplitude slightly less than the threshold current is applied, which raises the electron concentration close to threshold. A high-speed current pulse is then superimposed on this bias current. In practice a d.c. bias current cannot be used owing to power dissipation limitations, however a bias current can be applied for up to 200ns without any detrimental effects. This allows more than sufficient time for the electron density to reach an equilibrium level.

Figs. 3.6(a), (b) show the predicted response of a 5.5A laser biased to 90% of threshold and pulsed with a 10A, 1ns duration, and a 20A, 0.5ns duration half-sine current pulse. Just sufficient charge is injected by the 10A current pulse
Fig. 3.6(a) Theoretical response of a 5.5A threshold laser biased at 90 percent of threshold and pumped with a 10A, 1ns half-sine pulse.

Fig. 3.6(b) Theoretical response of a 5.5A threshold laser biased at 90 percent of threshold and pumped with a 20A, 0.5ns half-sine pulse.
Fig. 3.6(c) Theoretical response of a 5.5A threshold laser biased at 90 percent of threshold and pumped with a 20A, 1ns half-sine pulse.

to produce a single optical pulse. To achieve the same peak optical power without biasing, a peak current of over 50A would have been required. If the charge injected by the pumping pulse is increased then multiple oscillations might occur, Fig. 3.6(c).

It should be noted that the laser's temporal output is not now directly dependent on the pumping current pulseshape since the laser never reaches equilibrium. Therefore shot-to-shot variations in pulseshape, evident when operating with long duration current pulses, should not now occur.
3.3.2.4 Time Delay

A time-delay exists between the application of the current pulse and the occurrence of the laser output. An expression for the time-delay \( t_d \) can be obtained from eq.(3.1). Since the device is operating below threshold until \( t = t_d \), the photon density \( N_p \) is approximately zero and eq.(3.1) simplifies to:

\[
\frac{dN_e}{dt} = \frac{J}{q.d} - \frac{N_e}{T_s} \quad \text{......... (3.12)}
\]

The carrier concentration \( N_e \) above threshold is 'clamped' at a constant value (after any turn-on effects have diminished) just sufficient to provide enough gain to overcome the optical losses. The time behaviour of the carrier concentration until threshold is reached, is, from eq.(3.12):

\[
N_e(t) = \frac{J T_s}{q.d} (1 - \exp(-t/T_s)) \quad \text{......... (3.13)}
\]

The time-delay for the carrier concentration to reach \( N_{\text{eth}} \) is:

\[
t_d = T_s \ln \left[ \frac{I_p}{I_p - I_t} \right] \quad \text{......... (3.14)}
\]

Considerably longer time delays may be encountered in practice owing to the non-zero risetime of the current waveform. Fig.3.7 shows the computed time delays for a
Fig. 3.7 Time delay versus peak drive current for half-sine pulse.

Fig. 3.8 Relative time delay for a 5.5A threshold laser driven in 1A increments above threshold.
number of different pulsewidth half-sine shaped current pulses together with experimentally measured delays, as a function of peak drive current. The laser threshold current was 5.5A. Particularly good agreement is found between the measured and predicted delays for the Avtech pulser although for the Power Technology pulser measured delays were some 2-3ns longer than predicted.

A series of measured temporal responses obtained from the 5.5A threshold laser as the drive current was progressively increased above threshold is shown in Fig.3.8.

3.4 COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

3.4.1 Streak Camera Receiver

Figs.3.9,3.10 show the temporal response of the 5.5A threshold laser when driven with the Power Technology and short-pulse duration pulsers as taken with the streak camera. The peak drive currents were 25A and 35A and the time resolution 10ps and 80ps respectively. Since the streak camera makes a recording of a single optical pulse no pulse-to-pulse integration effects are present in Figs.3.9,3.10. The oscillations in the laser output predicted by theory are now clearly visible.

The corresponding theoretically predicted results are shown in Fig.3.3(a),(b). As can be seen there is good agreement between the two sets of results.

Fig.3.11 shows the shortest optical pulse which was recorded (≈ 90ps FWHM); it was generated with the laser
Fig. 3.9  Streak camera recording of laser output. Drive current 25A, 4ns, basewidth pulse. Time scale - 360ps per major division.

Fig. 3.10  Streak camera recording of laser output. Drive current 35A, 16ns, basewidth pulse. Time scale - 2.3ns per major division.
Fig. 3.11 Streak camera recording of shortest observed laser pulse. Time scale - 360ps per major division.
operated near threshold and driven with the short-pulse duration Avtech pulser.

3.4.2 Photodiode Receiver

In practice the limited bandwidth of the optical receiver used to detect the laser radiation will, of course, modify the observed signal. Fig.3.12 shows the predicted variation of peak optical power versus applied current, for half-sine current pulses of various pulsewidths, as would be perceived by a optical receiver of 400ps risetime. Again the calculations have been based on a laser with a threshold current of 5.5A. Also shown on the plot are experimentally obtained data points for the short-pulse duration Avtech and Power Technology pulsers.

The integrated optical outputs (ie the pulse energy) have also been obtained both experimentally and theoretically, the results obtained are shown in Fig.3.13. As can be seen from these Figures there is good agreement between the theoretical and experimental data.

Fig.3.14 shows the predicted temporal output when viewed with an optical receiver of risetime 400ps. The laser peak current is 25A and the pulse durations 5ns (Fig.3.14(a)) and 16ns (Fig.3.14(b)). The corresponding measured responses as obtained from the pulse shape data acquisition system described earlier are shown in Fig.3.15 (a summary of the other results obtained during the measurement programme are presented in Appendix 3.3).

For the short duration pulser very good agreement is
Fig. 3.12 Transfer characteristic for half-sine drive pulse and receiver risetime of 400ps.

Fig. 3.13 Integrated optical output characteristic for half-sine shaped drive pulse.
Photon/Electron Densities (Norm.)

Time (nanoseconds)

Electron Density

Photon Density

Average pulse envelope

Photon Density

b) drive current - half-sine pulse 25A 16ns duration

b) drive current - half-sine pulse 25A 16ns duration

Fig.3.14 Laser temporal response - receiver risetime 400ps
a) Avtech short pulse duration pulser - peak current 25A

b) Power Technology pulser - 25A peak current

Fig.3.15 Measured laser temporal response
found between the predicted (2.3ns) and measured (approximately 2ns) turn-on delay times. The basewidth of both predicted and measured pulses also agrees well. Slight shot-to-shot variations (visible on a 275MHz real-time oscilloscope as a blurring of the pulse) are averaged out by the sampling oscilloscope and consequently no 'ringing' is observed in the measured pulse. However if the oscillations on the predicted pulseshape are smoothed out then the resulting pulse envelope agrees well with the measured response (see dotted curve).

With the Power Technology pulser again allowing for the pulse-to-pulse variations, the overall pulseshape shows good agreement. However the turn-on delay is some 2-3ns longer in the measured than in the predicted case. The measured optical pulse also continues to lase after termination of the current pulse (this occurred with all the lasers when operated with the Power Technology pulser) indicating a possible time delay between the current pulse appearing at the pulser current monitor and laser sockets.

3.5 SUMMARY

A computer program has been written which solves numerically the coupled rate equations describing the behaviour of a laser diode. Using this program the theoretical performance of these devices has been examined in detail.

The results of the analysis have been compared with an extensive set of measurements of the behaviour of a number
of lasers under extremely fast pulsing conditions. The agreement has been found to be startlingly good. The idea of an effective threshold current, dependent on the temporal characteristics of the pumping current pulse, has been introduced which gives a more realistic estimate of the laser output power. The technique of pre-biasing the laser close to threshold before applying the short duration current pulse has been studied with the aid of computer simulation. Significant improvements in performance result in using this method of laser pumping.

An automated data acquisition system for sampling both the current and optical waveforms has been described which was used extensively in collecting much of the experimental data.

In conclusion, the behaviour of pulsed single heterojunction semiconductor diode lasers, when pumped with short duration current pulses, can now be estimated with a greater degree of certainty. This in turn allows the performance of laser diode rangefinders and imagers operating with nanosecond duration drive current pulses to be predicted with confidence.
CHAPTER IV

A LASER BASED TERRAIN MAPPER

4.1 INTRODUCTION

This chapter describes in detail the design and subsequent construction of a prototype terrain mapping and analysis system. An initial short feasibility study indicated that a semiconductor laser diode based system could meet the requirements specified by the project sponsors. The main objectives of designing this prototype equipment were twofold. Firstly, experience was required in the techniques necessary to design such an instrument before a fully engineered system was embarked upon. Secondly, as active imaging is very much in its infancy little information is currently available on the operational effectiveness of such systems in realistic environments. The prototype would provide such data from a wide variety of different targets and terrains. This database could then be used to evaluate the effectiveness of scene analysis algorithms which might ultimately be incorporated in the terrain mapper.

Ultimately the sensor will be incorporated on a 'roving' robotic vehicle and will provide navigational information. There is no requirement therefore to produce a pictorial display for interpretation by a human observer, so this topic is not covered here. The design philosophy then
has been to develop a static tripod-mounted optical assembly and associated electronics with the emphasis on providing a means for flexible acquisition of the range data. Areas such as high speed scanning of the laser beam and stabilization of the optical assembly, which would be required for a fully engineered instrument, have consequently not been investigated in this phase of the study.

The operational range requirements of the terrain mapper can be subdivided into two regions. For short and intermediate ranges (up to 25m) the equipment should be capable of measuring the local terrain slope. For longer ranges, where slope measurement is not practical, an obstacle detection capability is required.

The local terrain slope can be estimated by obtaining the range to the terrain location of interest, incrementing the beam pointing direction in the plane in which the slope is required, and performing a second range measurement. The geometrical arrangement is shown diagramatically in Fig. 4.1. The accuracy to which the terrain slope can be obtained is dependent on both the angle-pointing uncertainty and range measurement uncertainty. An analysis of how these factors affect the terrain mapper accuracy as a function of scanner height and range is given in Appendix 4.1. For terrain slope estimations in the range of interest here a ranging accuracy of the order of 15cm and an angle-pointing accuracy of 2 arc min are found to be required.

The operational performance of the instrument
LOCAL TERRAIN SLOPE =

\[ R_2 \cdot \sin(\theta + \Delta \theta) - R_1 \cdot \sin(\theta) = R_1 \cdot \cos(\theta) - R_2 \cdot \cos(\theta + \Delta \theta) \]

Fig. 4.1 Terrain slope estimation
described here is discussed in the following chapter.

4.2 THE RANGE MEASUREMENT

Several potential ranging techniques were briefly examined, including ultrasonic, millimetre wave, and optical. The first two candidates were rejected since neither could provide the required spatial resolution with an aperture of acceptable size. Although range information can be deduced from passive optical images (using, for example, stereoscopic images [McVey 1983]) these systems are cumbersome and require extensive signal processing to extract the range data. An active optical system can provide range directly and is eminently suitable for the application being considered here.
The choice of laser source for this application is quite straightforward. The pulsed single heterojunction laser by virtue of its small size, low cost, and simple power supply requirements is ideally suited.

To obtain range information the laser source must be modulated. Two obvious approaches suggest themselves:

1) Continuous wave amplitude modulation
2) Time-of-flight pulse ranging

4.2.1 Amplitude Modulation

By continuously modulating a c.w. laser source with a repetitive waveform and performing a phase comparison between the transmitted and received signals range information can be extracted. For unambiguous ranging the modulating wavelength must be greater than twice the maximum range of operation. Typical modulating frequencies for short range terrain analysis applications would be in the region of a few megahertz. Given that a phase accuracy of 0.5° can be achieved with reasonable care then a range accuracy of about 15cms could be obtained.

Although an acceptable range accuracy can be readily achieved, the c.w. method has two serious drawbacks. Firstly for a sinusoidally modulated carrier it is not possible to detect multiple reflections. For example, consider the situation where the laser beam partially intercepts a target with the remainder of the beam propagating to the terrain some distance behind. The sensor
would erroneously interpret this as a single target located at some range between the two sources of reflection.

A second more fundamental shortcoming arises from the optical detection process itself. Photodetectors are inherently 'square law' devices, that is their output voltage is proportional to the square of the incident electric field. For the c.w. case the optical signal-to-noise ratio (i.e. that prior to detection) is low, since a low peak-power signal is embedded in wideband background noise. Only after detection can the wideband noise be effectively rejected.

The output signal plus noise after detection \((s_d + n_d)\) is related to the input signal plus noise \((s_i + n_i)\) for a photodetector by:

\[
s_d + n_d = s_i^2 + n_i^2 + 2s_in_i \quad \ldots \ldots (4.1)
\]

hence the signal-to-noise ratio after detection can be expressed as:

\[
\frac{s_d}{n_d} = \frac{s_i^2}{2s_in_i + n_i^2} \quad \ldots \ldots (4.2)
\]

When the input signal-to-noise ratio is much less than unity then eq. (4.2) reduces to:

\[
\frac{s_d}{n_d} = \frac{s_i^2}{n_i^2} \quad \ldots \ldots (4.3)
\]
It is evident from eq.(4.3) that when the SNR is poor (i.e. less than unity) the detection process degrades it. However, when its good the input and output SNR's are linearly related:

\[ \frac{s_d}{n_d} = \frac{s_i}{2n_i} \quad \ldots \ldots (4.4) \]

Hence to maintain the signal-to-noise ratio after detection a high peak power is advantageous. Input SNR's will be, for a c.w. scheme of average power \( P_{av} \), lower by a factor of

\[ \frac{P_{peak}}{P_{av}} \quad \ldots \ldots (4.5) \]

compared with a pulsed modulation system of equal average power.

4.2.2 Pulsed Ranging

Time-of-flight pulse ranging has been used extensively in the past for a number of ranging applications, and in particular for military rangefinders operating at ranges in excess of 5 kilometres. At these distances a range accuracy of a few metres is usually adequate. Typically the time delay between transmission and reception of the leading edge of the laser pulse is measured using some form of time interval counter. At shorter ranges where a greater range accuracy is required the clock pulse counting method becomes difficult owing to the high clock frequency involved. An
alternative approach, adopted here, is to use a linear ramp (triggered on transmission and terminated on reception) to perform a time-to-voltage conversion.

Operation in the time domain allows multiple target returns to be detected easily providing the target separation is greater than:

\[
\frac{c.t}{2} \quad \ldots .(4.6)
\]

where \( t \) is the laser pulsewidth

As in the c.w. scheme, the maximum repetition rate of the modulating waveform should be less than the reciprocal of the two-way propagation time to avoid ambiguities. The maximum pulse repetition frequency (p.r.f.) is therefore

\[
p.r.f._{\text{max.}} = \frac{c}{2R_{\text{max}}} \quad \ldots .(4.7)
\]

4.2.3 The Range Equation

The received optical power from an extended Lambertian scatter will, if all the received power is detected, obey an inverse square-law range dependency. The range equation for this case takes the following form:

\[
P_{sr} = \frac{P_t T_t A_r \rho \cos \theta \exp(-2\sigma R)}{R^2} \quad \ldots .(4.8)
\]
where

\[ P_{sr} = \text{received signal power (W)} \]
\[ P_t = \text{peak transmitter power (W)} \]
\[ A_r = \text{area of receiving optics (m}^2\text{)} \]
\[ p = \text{diffuse target reflectivity} \]
\[ T_t = \text{transmittance of transmitter optics} \]
\[ \varnothing = \text{target/laser beam angle} \]
\[ \sigma = \text{extinction coefficient (m}^{-1}\text{)} \]
\[ R = \text{range to target (m)} \]

If the target intercepts only part of the transmitted beam then the received power as predicted by eq.(4.8) should be reduced by a factor of

\[ \frac{4 A_t}{R^2 \varnothing_t} \]

where

\[ A_t = \text{target area} \]
\[ \varnothing_t = \text{transmitted beam full angle divergence} \]

If the receiver is focused for all ranges of interest then the optical power intercepted by the photodetector is

\[ P_{sd} = T_r P_{sr} \quad \ldots \quad (4.9) \]

where \( T_r \) is the transmittance of the receiving optics. The square-law nature of the optical detection process results in an output signal current \( (i_s) \) from the photodetector of
where

\[ R_e = \text{photodetector responsivity} \]
\[ G = \text{pre-detection gain} \]

and an output voltage developed across a load resistance \( R_p \) of

\[ V_s = P_{sd} G R_e R_p \quad \cdots \quad (4.11) \]

It is informative at this stage to substitute some typical values into eq. (4.11) and (4.9) in order to estimate the magnitude of the photodetector output voltage.

In order to gain an appreciation of the likely variations of terrain reflectivity as a function of aspect angle, target reflectivity data has been collected for a number of both man-made and natural materials. A description of the measurement system developed for this purpose is given in Appendix 4.2. A typical albedo for natural terrain environments of 0.4 will be used here.

The following values will be used for the other parameters in the range equation:

\[ P_t = 2 \text{ W} \]
\[ A_r = 0.0078 \text{ m}^2 \]
\[ p = 0.4 \]
\[ T_r = 0.9 \]
\[ T_t = 0.9 \]
\[ R_e = 0.6 \]
\[ G = 50 \]
\[ R_p = 50 \text{ ohms} \]
\[ \sigma = 86.5^\circ \]
\[ R = 25 \text{ m} \]
\[ \sigma = .2 \text{ km}^{-1} \]

Using the above values \( v_s \) is found to be :-

\[ 230\mu V \text{ (peak)} \]

It is now necessary to consider the various noise mechanisms which are present.

### 4.2.4 Noise Sources

Noise will originate from the following principal sources :-

1) Signal shot-noise
2) Background shot-noise
3) Thermal noise
4) Excess noise (owing to the avalanche gain)

#### 4.2.4.1 Signal Shot Noise

The fundamental limit on signal-to-noise ratio is governed by the quantum nature of the received signal pulse. The signal-induced current squared shot-noise is :-

\[ i_{ns}^2 = 2 i_s q \text{ B} \]

\[ .......... \quad (4.12) \]
where

\( i_s = \text{signal photocurrent} \)

\( q = \text{electronic charge} \)

\( B = \text{electrical bandwidth} \)

and since the photocurrent is related to the incident optical power by:

\[
i_s = P_{sd} \frac{R_e}{G}
\]

the signal shot-noise component in terms of detected power is:

\[
i_{ns}^2 = 2qB P_{sd} \frac{R_e}{G} \quad \cdots \cdots \cdots \quad (4.13)
\]

**4.2.4.2 Background Noise**

Scattered solar radiation within the field-of-view of the receiving optics will be detected along with the desired signal component. The detected solar background power \( P_{bd} \) is given by:

\[
P_{bd} = \frac{A_r B_{opt} T_r H_w \Omega_r P}{\pi} \quad \cdots \cdots \quad (4.14)
\]

where

\( B_{opt} = \text{optical filter bandwidth (nm)} \)

\( H_w = \text{solar irradiance (Wm}^{-2}\text{nm}^{-1}) \)
\( \Omega_r = \text{receiver FOV (sr)} \)

It is evident from eq.(4.14) that spectral filtering and a narrow receiver field-of-view are required to limit the background power reaching the detector. Using the previous values and for

\[
B_{\text{opt}} = 20 \text{ nm} \\
H_w = 0.5 \text{ Wm}^{-2}\text{nm}^{-1} \\
\Omega_r = 0.1 \text{ millisteradian}
\]

the detected background power is found to be

\[
P_{bd} = 900 \text{nW}
\]

This background power will cause shot-noise to be generated at the detector output. The magnitude of the noise is, as for the signal shot-noise case

\[
i_{\text{nb}}^2 = 2 I_b q B \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4.15)
\]

where

\( I_b = \text{background photocurrent} \)

and in terms of the detected optical power :-

\[
i_{\text{nb}}^2 = 2 q B P_{sd} R_e G \quad \ldots \ldots (4.16)
\]
4.2.4.3 Thermal Noise

The preamplifier will generate noise due to a number of mechanisms and these can be lumped together and an equivalent input noise current \( i_a \) can be used to represent the amplifier noise.

4.2.4.4 Excess Noise

Detectors operating in the avalanche mode produce additional noise owing to a gain dependant noise process within the detector. The noise term for a avalanche photodetector is proportional to:

\[
G^{(2+x)} \quad \ldots \ldots (4.17)
\]

where \( x \) = excess noise factor

4.2.5 Signal to Noise Ratio

The total mean square noise contribution at the output of the photodetector preamplifier is given by:

\[
i_n^2 = 2 q B R_e (P_{sd} + P_{bd}) G^{(2+x)} + i_{na}^2 \ldots (4.18)
\]

where \( i_{na} = i_a \sqrt{B} \)

and the root mean square (RMS) noise voltage, \( v_n \) is given by

\[
v_n = R_p \left( 2 q B R_e (P_{sd} + P_{bd}) G^{(2+x)} + i_{na}^2 \right)^{1/2} \ldots (4.19)
\]

Combining eq. (4.11) and (4.19) yields an expression for the voltage signal-to-noise ratio:
If we consider the case where the dominant noise is that due to shot-noise then the SNR becomes:

\[
\frac{v_s}{v_n} = \frac{P_{sd} R_e G}{(2 q B R_e (P_{sd} + P_{bd}) G^{(2+x)} + i_{na})^{1/2}} (4.20)
\]

We can now estimate the SNR, using the values given previously, for two cases of interest:

a) slope measurement at 25m range
b) obstacle detection at 50m

Case (a)

For horizontal terrain and a 2m scanner height we obtain from eq. (4.8) and (4.9)

\[
P_{sd} = 80 \text{ nW}
\]

The background power, \(P_{bd}\), was calculated earlier to be in the region of 900nW, so for an APD gain of 50 (this will ensure that the system is shot-noise limited), an excess noise factor of 0.3 and a bandwidth of 500MHz we obtain a SNR of approximately 5:1.

Case (b)

For obstacle detection at 50m we will assume \(\cos\theta\) to
be approximately unity, and so the detected power now becomes:

\[ P_{sd} = 250 \text{nW} \]

and the signal-to-noise ratio becomes 14:1.

4.2.6 Range Accuracy

The accuracy to which the position of the terrain or an obstacle can be determined is governed by several factors. Essentially the problem can be reduced to that of determining the time location of a pulse in the presence of noise.

The commonly adopted technique is to observe the time at which the front edge of the received pulse crosses a threshold level. If the risetime of the leading edge is \( t_r \), then the timing jitter \( \sigma_t \) is given by:

\[ \sigma_t = \frac{t_r}{\text{SNR}} \quad \ldots \ldots (4.22) \]

Hence the maximum timing uncertainty is in this case approximately equal to the receiver risetime.

The ranging accuracy can be improved by integrating a number of independent measurements, in which case an improvement in accuracy of \( \sqrt{n} \) can be achieved over a single pulse measurement.
4.3 THE TERRAIN MAPPER HARDWARE

The terrain mapper system subdivides into two segments, the optical subsystem, which is tripod mounted and comprises of the transmitter and receiver optics and associated electronics, and the electronics subsystem which is housed in a small modular racking unit. The terrain mapper is shown diagrammatically in Fig. 4.2. A brief description of the equipment is given in the following sections.

4.3.1 Terrain Mapper Optical Subsystem

The optical segment comprises of the following main components:

1) Laser pulser and membrane beamsplitter
2) PIN photodiode 'start pulse' detector and preamplifier
3) 10cm dia. (10cm f.l.) Fresnel receiving lens with inset 25mm (25mm f.l.) laser collimating lens
4) Bandpass interference filter - nominal centre wavelength 904nm +/-10nm
5) Avalanche photodiode (RCA No. C30948E) and preamplifier module
6) Proportional DC/DC voltage converter for APD bias
7) motorised 16.5cm by 11.5cm plane mirror beam deflector

All the above components are contained within a 50cm by 26cm
Fig. 4.2 Block diagram of the terrain mapper.
by 26cm case. The completed assembly (with the protective case removed) is shown in Fig. 4.3.

4.3.1.1 Laser Transmitter

The transmitter comprises a single heterojunction pulsed semiconductor laser driven by a Power Technology (model no. IL40C) pulser, membrane beamsplitter, and collimating lens.

For a given source size, the illuminated area at the target is determined by the focal length of the collimating lens.

That is by

\[
\frac{R S_h}{f} \quad \ldots \quad (4.23)
\]

and in the orthogonal plane by

\[
\frac{R S_w}{f} \quad \ldots \quad (4.24)
\]

where

- \( f \) = focal length of lens
- \( S_w \) = source width
- \( S_h \) = source height

The pulser is capable of delivering current pulses of 30A peak and 10ns halfwidth duration. The laser selected has a source size of 100\( \mu \)m by 2\( \mu \)m and a maximum peak current rating of 12A (rated at 200ns pulse duration). It is
Fig. 4.3 Terrain mapper optical subsystem
permissible to use this laser since the maximum drive current can be uprated when using pulses of less than 200ns duration. Details of the permitted degree of uprating are given in Appendix 4.3.

The laser output is collimated by a 25mm diameter, 25mm focal length lens. This gives an illuminated area of 10cm by 0.2cm at a range of 25m. A 25mm diameter membrane beamsplitter is mounted directly onto the front of the laser pulser. The beamsplitter is 8µm thick and therefore produces no distortion of the optical pulse. At an incident angle of 45°, 90% of the beam is transmitted.

The laser pulser is mounted on a small sliding carriage enabling focusing, azimuth, and elevation adjustments to be performed.

4.3.1.2 Laser Pulse Monitor Photodetector

A small portion (approximately 10%) of the outgoing laser pulse is deflected by the beamsplitter onto the monitor photodiode (Hewlett Packard No.4220, 0.5mm dia, 0.5ns risetime). A 5mm diameter plastic lens is used to increase the detection sensitivity. Two Avantek 400MHz bandwidth, 13dB gain amplifiers follow the photodetector. The signal-to-noise ratio at the output of the second amplifier typically exceeds 50dB. This signal is fed directly to the start channel of the timing module.
4.3.1.3 Receiving Optics

The receiving lens is a 10cm diameter Fresnel type lens with a focal length of 10cm. The photodetector is an avalanche silicon photodiode with an active diameter of 0.8mm. This combination results in a receiver field-of-view of 8mR. A 'side-by-side' optical arrangement has been adopted for the transmitter and receiver optics as the obscuration which would have been caused by a coaxial configuration would have resulted in a significant signal loss at close range (see Appendix 4.4).

The photodetector and its associated preamplifier are mounted in a 7.5cm by 4.5cm by 2cm case which in turn is mounted on a sliding carriage to facilitate alignment. The photodetector output is amplified by two Avantek amplifiers (types GD401 and GD402) which provide a gain of 26dB.

4.3.1.4 The Scanner

The scanner consists of a small tilt and rotate stage (Ealing No. 22-8163) upon which is mounted a 16.5cm by 11.5cm front-aluminized plane mirror. The maximum angular travel, in either direction, is +/- 5°. Two stepper motors (Phillips no. 9904-115-23101) are used to drive the stage. Both motors are driven in the half step mode which gives a motor step angle of 0.9°. The gearing of the stage results in a basic mirror step angle of approximately 50 microradians.
4.3.2 Terrain Mapper Electronics Subsystem

The majority of the electronic modules are mounted in a 'Eurocard' racking system. This allows for additional modules to be easily added to the system. The completed electronics unit is shown in Fig. 4.4. All circuit diagrams for the terrain mapper are given in Appendix 4.5.

4.3.2.1 Timing Circuit

The function of the timing board is to produce a 10 bit binary word proportional to the time delay between pulses appearing at the 'start' and 'stop' inputs. The circuit consists of two parallel channels, identical in nature, which are used to:

a) trigger a ramp waveform on detection of a pulse at the 'start' input

and then

b) trigger a track and hold circuit to sample the ramp on detection of a pulse at the 'stop' input

As both channels are identical any small variations in propagation time due to temperature fluctuations affect both channels in a similar manner. The input to the 'start' channel is derived from a PIN photodetector which monitors the optical output of the laser. By monitoring the actual transmitted optical pulse, as opposed to the stimulating current pulse, variations in propagation delay within the laser and the pulser cannot affect the timing accuracy.
b) Circuit boards

Fig. 4.4 Terrain mapper electronics unit
Inputs to both channels are fed directly to a dual high-speed voltage comparator (Advanced Micro Devices model no. AMD 687).

The input threshold level for the 'start channel' can be varied from near 0V up to a few hundred millivolts by a preset control. When the threshold level is exceeded the comparator output triggers a monostable which latches the comparator output in the 'high' state for a period corresponding to the maximum delay time, in this case approximately 400ns. The output pulse from the comparator is converted to TTL logic levels and applied to an open collector NAND gate which functions as a switch forming part of the ramp generator circuit.

A linear time/voltage ramp is produced by charging a capacitor from a constant current source. The voltage developed across the capacitor is given by:

\[ V_o = \frac{I_c t}{C} \]  \(\text{(4.25)}\)

where

- \(I_c\) = constant current (A)
- \(t\) = time from start of ramp (ns)
- \(C\) = charging capacitance (nF)

The constant current, \(I_c\), is generated as follows. A precise low temperature coefficient voltage reference source, derived from three ZN423's is used to bias the
non-inverting input of a LM308A high performance operational amplifier. The voltage developed across a current sensing resistor, $R_s$, is compared with the reference source and any discrepancy produces an error voltage which tends to restore the current to a value of:

$$I_c = \frac{V_{\text{ref}}}{R_s} \quad \ldots \ldots \ldots (4.26)$$

With the input to the NAND gate at logic '1', as occurs prior to a pulse being applied to the 'start' input, the output transistor of the gate is switched on thereby bypassing current from the ramp capacitor. When the gate changes state the current flows through the capacitor producing a ramping voltage. The ramp waveform is shown in Fig.4.5. A high-speed buffer isolates the ramp generator from the track-and-hold module.

The principal sources of temperature drift that occur are due to the voltage reference source (30 ppm/°C) and the current sense resistor (precision wirewound 10 ppm/°C). The operational amplifier introduces virtually no additional drift.

The temperature coefficient of the current source was measured as 30ppm/°C.

The temperature stability of the ramp is also dependant on the charging capacitor stability. A high stability palladium/ceramic (+/- 30ppm/°C) capacitor is therefore used to minimize drift.
Fig. 4.5 Timing ramp waveform

Fig. 4.6 Laser 'burst' trigger signal
The threshold level of the 'stop' channel can be set from 0mV to 20mV. The functions of the first stages are similar to the 'start' channel. In this case however the monostable latches the comparator outputs for 30 microseconds (the time required to perform the A/D conversion). After passing through the level translator and NAND gate this transition triggers the track-and-hold circuit.

For the track-and-hold being used here (Analog Devices HTC-300) the aperture uncertainty, a measure of the timing jitter, is 100ps. The analogue-to-digital conversion is performed by an Analog Devices ADC-80 configured as a 10bit converter. The conversion time is less than 25us. An inverting amplifier interfaces the track-and-hold with the A/D converter enabling the full range of the converter to be utilized.

If no pulse is received at the 'stop' input before the end of the ramp waveform the track-and-hold is not put into the 'hold' condition, but an A/D conversion is still initiated. The A/D converter in this situation returns a null value of '0'. On completion of the A/D conversion process, a 'data-valid' signal is generated which initiates the transfer of the data, via the computer interface, to the desk-top computer.

Owing to the very high gain and speed of the ECL comparators (60dB at 100MHz) considerable care was required in circuit construction and layout. A ground plane was used to ensure a low impedance current return path. In addition
the ground plane forms the backing for the microstrip transmission lines used for interconnections between the emitter-coupled-logic integrated circuits.

4.3.2.2 **Scan Frame Formater**

The scanning of the terrain mapper is normally controlled by the Scan Frame Formater. This frees the computer from the task and allows higher scanning speeds to be achieved. The scanning speed is limited, by the mechanics of the scanner, to about 5° per second.

The Formater produces all the necessary signals for controlling both stepper motors and also for firing the laser. Prior to commencement of a scan the frame parameters are sent from the computer and are stored in data registers within the Formater.

These parameters are:

1) $N_1$ - Clock division ratio.
2) $N_2$ - Number of scanner steps between pixels.
3) $N_3$ - Number of laser pulses per pixel.
4) $N_4$ - Number of pixels per line.
5) $N_5$ - Number of lines per frame.

The clock operates at a frequency of 10kHz, which is the maximum rate at which the laser pulser can function. The stepping speed of the azimuth motor is therefore $10\text{kHz}/N_1$. After the azimuth motor has moved $N_2 \cdot (10\text{kHz}/N_1)$ steps, that is the distance between pixels, the laser is
fired $N_3$ times at a rate of 10kHz. The maximum number of shots in the burst is limited to 15. An oscilloscope trace of the laser trigger signal for a burst of 4 shots is shown in Fig.4.6.

This sequence is repeated $N_4$ times whereupon the azimuth motor direction is reversed and the elevation motor is stepped $N_2^*(10kHz/N_1)$ times. The scan proceeds as above until the elevation motor has been stepped $N_5$ times. Control of the stepper motors is then passed to the computer. The scanner can now either be returned to the original starting position or a new starting point may be selected. The computer can also independently 'power down' the motors between scans (no holding torque is required to maintain position) if required.

4.3.2.3 Stepper Motor Drivers

The scanner position is controlled by two stepper motors. These motors are driven by a R/L type half-step control circuit based on VMOS transistor switches. The scanner motors can either be driven directly from the computer, in which case any arbitrary scan pattern can be generated, or from the scan frame format when high speed rectilinear scanning is required. The control codes for driving the motors directly from the computer are given in Appendix 4.6.
4.3.2.4 Computer Interface

The computer interface board allows the terrain mapper to connect directly onto any IEEE-488 standard data bus.

All interactions with the IEEE bus are controlled by a Signetics IEEE bus interface integrated circuit (no. HEF4738). This chip provides all the necessary bus handshaking signals which are connected to the bus via four quad bi-directional transceivers.

Up to 16 different commands can be sent (corresponding to the ASCII characters @ to 0 inclusive) to the unit. The interface has three 8 bit output ports configured as follows.

Ports 1 and 2 are used to return the 10 bit digital range word to the computer over the 8 bit data bus. Six bits of this 16 bit word are uncommitted and may be used to return status information if required. In the 'range data transfer' mode operation is as follows. When the interface is addressed to 'talk' (i.e. to transmit data) the upper two bits (Port 1) of the range data are placed on the bus. When the interface is addressed to 'talk' a second time the remaining 8 bits (Port 2) are placed on the bus. The computer can now reconstitute the original 10 bit data word.

Port 3 is an auxiliary port which may be selected by sending the ASCII character "A" to the unit. Now when the unit is next addressed to 'talk' the auxiliary port data is transmitted back to the computer. The auxiliary port is disabled by resending the ASCII character "A".
4.3.2.5 **Power Supply**

The power supply consists of two parts, a mains input 12V 5.6A PSU and a converter unit which develops the various voltages required to power the equipment. This arrangement was adopted to enable the equipment to be powered from a 12V battery source if required.

The various power supply requirements for the equipment are summarized in Table 4.1.

<table>
<thead>
<tr>
<th>VOLTAGE</th>
<th>CURRENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>+/-15V</td>
<td>150mA</td>
</tr>
<tr>
<td>+5V</td>
<td>1.5A</td>
</tr>
<tr>
<td>-4.2V</td>
<td>500mA</td>
</tr>
<tr>
<td>-2.0V</td>
<td>250mA</td>
</tr>
<tr>
<td>+12.0V</td>
<td>2A</td>
</tr>
<tr>
<td>220-330V</td>
<td>10mA</td>
</tr>
</tbody>
</table>

Table 4.1 **Power Supply Requirements**

The +5V supply is derived using a conventional series regulator. The remaining supplies are generated using switching mode regulators. Owing to the inherent switching action of this type of regulator, significant noise can appear on the output lines. This is normally reduced to an acceptable level by capacitive smoothing, however for the level of ripple voltages required here the capacitance values become excessive. An alternative approach to
reducing the switching noise has been adopted here. The output of the switching regulators is set 3-4V higher than required and only minimal capacitive smoothing is provided (to reduce the ripple to approximately 0.5V). An appropriate series regulator is then used to give the required output voltage. Although this is achieved with some loss in overall efficiency, an extremely clean supply is produced thanks to the high ripple rejection of the series regulators (typically 60dB). In case of regulator malfunction all supplies are over-voltage protected. If an over-voltage fault condition arises, defined here as being 1.5V above the normal operating voltage of the supply, then the output voltage is shorted to ground within 10μs.

The avalanche photodetector requires a bias voltage in the region of 230-330V, the actual voltage being dependant on the individual detector. This voltage is obtained by means of a D.C./D.C. converter module (Venus Scientific, model no. C8T). For an input voltage in the range 5-12V a proportional H.T. voltage of 150-400V is obtained.

4.4 SUMMARY

The design and construction of a prototype instrument capable of performing terrain slope measurements at ranges up to 25 metres has been described. No insuperable design problems were encountered when developing the instrument. The equipment has performed satisfactorily both in the laboratory and during field trials.

The range measurement is performed by a pulsed
semiconductor laser diode based optical rangefinder. For a maximum operating range of 50 metres the rangefinder can achieve, with a good signal-to-noise ratio, a range accuracy of better than 5cms.

Owing to the design complexity of high-speed large aperture optical scanners it was decided at an early stage that this area would not form part of the current programme of work. Consequently a mechanically simple low-speed mirror scanner has been incorporated into the terrain mapper. This, however, still enables the primary objectives of the project to be achieved, namely the evaluation of a terrain mapping system operating in realistic environments.

After some preliminary measurements performed from the laboratory site the equipment underwent field trials at the project sponsor's establishment. The performance of the equipment is described in the next chapter.
CHAPTER V

PRELIMINARY RESULTS FROM THE TERRAIN MAPPER

5.1 INTRODUCTION

The aim of this chapter is to present, mainly in graphical form, results obtained from the initial commissioning tests of the terrain mapper system described in the last chapter. As was outlined in chapter 4 the terrain mapper was designed principally as an instrument for gathering range data. No facilities have been incorporated in the present instrument for either data analysis or pictorial display. Consequently all data collected by the instrument has been transferred to the University's central computers for processing.

5.2 OPERATION OF THE TERRAIN MAPPER

The terrain mapper can be operated in one of two modes. In the 'direct transfer' mode the computer (the HP85) directly controls the functions of the terrain mapper. (A list of control codes for the instrument is given in Appendix 4.6). The speed of operation in this mode is fairly slow since, in addition to reading in the range data, the computer must issue commands to control the scanner and also to trigger the laser pulser. Owing to the slow input/output capability of the computer when running the BASIC computer language overall reading rates are typically
less than 5 readings per second in this mode. However, it is possible to generate any arbitrary scanning pattern.

The second operating mode is termed the 'fast handshaking' mode (FHS). In this mode a high-speed rectilinear scan is generated by the scan frame formater (see section 4.3.2.2). Prior to commencement of the scan the frame parameters are sent and stored in the terrain mapper. All motor scanning and laser trigger signals are now generated directly by the terrain mapper and during the scan the computer only has to read in range data, resulting in a significant speed increase. The data storage format for the FHS mode transfer is given in Appendix 5.1.

A listing of the terrain mapper control program is given in Appendix 5.2.

5.3 PRELIMINARY RESULTS

This section subdivides into two parts. Firstly some results are presented which were obtained during the initial setting up of the instrument in the laboratory. The targets used in these tests were typical of those which would be found in an urban terrain mapping environment, i.e. concrete, brickwork, metallic posts etc.. The second part of this results section reports on the operation of the equipment during field trials. The location chosen for the trials provided a variety of natural targets such as gravel paths, trees, bushes etc..
5.3.1 Results from the laboratory

The terrain mapper was located in the laboratory which has an open view onto a neighbouring roof some 23 metres away on the same level. The visual scene from the laboratory is shown in Fig.5.1.

Fig.5.2 shows the received signal from several of the objects visible from the laboratory window. The laser diode used was a 5.5A threshold device operated at a peak current of approximately 30A. Peak transmitted power, after beamsplitter and collimating lens losses, was approximately 2W.

The received signals depicted in Fig.5.2 were obtained before the optical filter was incorporated into the instrument, hence the large noise component (the output thermal noise level of the preamplifier is approximately 2mV p/p).

5.3.1.1 Slope Measurement

To illustrate the capabilities of the mapper at short range a vertical scan was taken of the roof directly outside the laboratory. The area comprises of concrete paving stones extending to the roof edge some 7m away. An interesting feature of this scene is a cornice at the roof edge (see Fig.5.1(a) foreground).

The mapper was set at a height of 1m with an initial beam pointing angle of 12° from the horizontal. The scan step angle was set to 0.1° with 8 laser pulses transmitted per pixel (the scan rate is independent of the number of
Fig. 5.1(a) View from the laboratory

Fig. 5.1(b) View from the roof above the laboratory
a) Brick wall (yellow) at 55m  b) Concrete wall at 35m  
c) Concrete wall at 23m  d) Grey painted post at 7m

Fig. 5.2 Typical Signal Returns (time scale 50ns/div. amplitude scale 20mV/div. (.d) 100mV/div.)
laser pulses per pixel). Fig.5.3 shows the measured range as a function of elevation pointing direction. Since in this case adjacent range readings are only separated by about the quantization level of the time/range convertor the range data has been low-pass filtered to remove the quantization noise. As can be seen the vertical cornice shows up clearly as a region of zero gradient (on a range/angle plot).

The corresponding terrain slope profile (where the slope has been expressed in 'degrees from the horizontal') is shown in Fig.5.4.

5.3.1.2 Horizontal Scan

Fig.5.5 shows the range profile resulting from a horizontal scan taken from the laboratory. The start position for the scan was just to the left of the railing post marked with two white tapes (Fig.5.1(a)). Beam step angle was 0.1° and the number of laser shots per pixel was 8. Again the range is plotted against beam pointing direction.

The first feature which is detected is the railing post at 7m. The next target to be detected is the extraction tower at a range of 35m. A progressive increase in range is measured as the tower is scanned (only just visible on this scale but easily detectable from the original range data) due to the tower being offset from the normal direction. A partial drop-out (pixel no.75) can be seen caused by one of the eight laser pulses failing to
Fig. 5.3 Slant range versus elevation beam pointing direction

Fig. 5.4 Terrain slope versus elevation beam pointing direction for the data of Fig. 5.3
Fig. 5.5 Horizontal scan of roof top
exceed threshold. The transition region between the two extraction towers (pixel no. 82) causes a complete signal drop-out owing to the laser beam striking both targets simultaneously resulting in neither return being of sufficient magnitude to trigger the timing module. Once the beam is fully onto the rightmost tower the end face can be discerned (pixels 85 to 95) with a 2 out of 8 drop-out occurring at the tower corner. A second post is detected (pixel no. 112) before the scan halts mid-way along the tower.

5.3.2 Summary of results from field trials

Fig. 5.6 shows the terrain mapper in operation during the field trials. Three of the locations used in these trials are shown in Figs. 5.7-5.9.

The scene visible from the first location (Fig. 5.7) comprises of an upward sloping stone/gravel track some 10m wide bearing around to the left. The track is surrounded by woodland. Two leaf-covered gravel mounds, located one behind the other, are present on the left hand side of the track (just visible on the right-hand side of Fig. 5.7). A large tree is located just off the left-hand side of the track. With the trials being performed in the winter months little foliage was present on the trees, although some decaying leaf mould was present on the ground.

Fig. 5.10 shows the measured terrain height as a function of azimuth and elevation beam pointing directions. The area of coverage is 4° (az.) by 2° (el.) with the
Fig. 5.6 View of terrain mapper in operation during field trials

Fig. 5.7 Field trials terrain location No.1
Fig. 5.8 Field trials terrain location No.2

Fig. 5.9 Field trials terrain location No.3
start of the scanned area being near the base of the tree in
the foreground of Fig.5.7. The terrain height, relative to
the terrain height at the base of the scanner is,

\[ T_h = H - R \sin \phi \] .... (5.1)

where \( \phi \) = the angle from the horizontal

\( H \) = scanner height

Fig.5.11 shows the same data transposed and displayed on an
azimuth v range v terrain-height plot. Some interpolation
has been incorporated in the plot since not every
azimuth/elevation co-ordinate has a corresponding
azimuth/range co-ordinate. The main features of the scene
can be recognised from Fig.5.11. The tree, azimuth beam
pointing directions 1-12, shows up clearly as does the
general profile of the terrain.

Fig.5.12(a) shows a single vertical line scan taken up
the track and scanning over the two gravel mounds on the
left-hand edge of the track. Again the data has been
low-pass filtered to remove the quantization noise. The
jump in the range plot (beam-pointing direction no.18)
occurrs when the laser beam leaves the top of the first mound
and then has to travel some distance before intercepting the
terrain again. This characteristic - a near zero gradient
region followed by a vertical jump in range is typical of
small obstructions. The corresponding terrain slope plot is
shown in Fig.5.12(b). Each symbol shown on the plot
Fig. 5.10 Terrain height v azimuth v elevation beam pointing directions

Fig. 5.11 Terrain height v azimuth v range
a) Range v elevation pointing direction

b) Slope v terrain range plot for range data of a)

Fig5.12 Range and slope plots for terrain location no.1
indicates the position of a range reading. The steeper first mound registers a maximum slope of some 40-45°.

A series of horizontal scans were performed through a heavily wooded thicket (Fig. 5.9) adjacent to the track. Fig. 5.13 shows a horizontal scan taken of the region around the large tree present in the foreground some 4m from the terrain mapper. The azimuth beam pointing step-angle in this case is 0.2° per pixel.

Fig. 5.14(a) shows a range versus elevation beam pointing direction plot taken at terrain location No.3. The step-angle in this case is 0.05°. Five laser pulses were transmitted per beam pointing direction and each individual range v elevation data file has been plotted to indicate the variations in ranging accuracy. The average of the 5 traces is shown in Fig. 5.14(b) (also shown is a low-pass filtered plot of the averaged data).

The effect of varying the angle increment used in the slope calculation is illustrated in Fig. 5.15. Use of the basic 0.05° increment, Fig. 5.15(a) results, as expected, in considerable slope errors since the spacing (in range) of adjacent beam pointing directions is only of the order of 10cm. The use of a 0.5° increment, Fig. 5.15(d), which gives approximately a 1m ground spacing reduces the error to only a few degrees.
Fig. 5.13 Horizontal scan through thicket
Fig. 5.14a) Range vs elevation pointing direction for terrain location no. 3 (5 traces).

Fig. 5.14b) Averaged and smoothed range data.
Fig. 5.15 Slope v range plot for terrain location no. 3 for various angle increments.
5.4 SUMMARY

The operation of a laser-based terrain mapper has been demonstrated against a variety of targets. To assess fully the operational performance of an equipment such as this an extensive test and evaluation programme, with the equipment being operated in many different environments is obviously required. Time has precluded such a detailed study from being included in this thesis.

It is evident from the figures presented here that interpreting the data is not always easy. A good deal of further work needs to be carried out in this area. (A 2 year evaluation programme, based on the encouraging preliminary results obtained from this present study, will commence shortly to look at, in particular, techniques for processing the data produced by the terrain mapper).

However, even from the thus-far, limited operation of the equipment some general remarks can be made.

Adequate sensitivity can be achieved against most types of targets with the system parameters as outlined in chapter 4, although at near maximum range (25m) targets of low reflectivity provided insufficient received signal to initiate a timing measurement. Basically there are two options which can be considered for increasing the system sensitivity. Either the transmitter power or the receiver aperture can be increased. The second option is unattractive since it would not only increase the overall size of what is at present a compact instrument, but also
make more complex and expensive the construction of the high speed scanning unit required for a fully engineered model. However, there does appear to be some scope for increasing the laser output power as outlined in chapter 3.

Operation of the terrain mapper has shown that the required ranging accuracy for terrain mapping applications can be easily achieved using fairly simple ranging techniques. The inherently fast pulse risetimes obtainable from laser diodes provide a well defined reference point for determining the time of arrival of the received pulse. As only the front edge of the pulse is used in the range measurement short duration pulses are beneficial - again this topic has been covered in detail in chapter 3.

In conclusion, the gathering of terrain feature information, so difficult to obtain by other techniques, can be effectively achieved using an equipment of the type described here. However, presenting the information in such a form that it can be assimilated easily is an area which requires further study.
REFERENCES


ADAMS M.J. 'Rate equations and transient phenomena in semiconductor lasers' Opto-Electronics Vol.5 p201-15 1973


BRIDGES T.J. et.al. 'CO$_2$ waveguide lasers' Appl. Phys.
BROOKNER I. 'Limit imposed by atmospheric dispersion on the maximum pulsewidth that can be transmitted undistorted' Proc. IEEE (Letters) Vol.57 p1234-5 1965


CHOWN M. et. al. 'Direct modulation of double heterostructure lasers at rates up to 1GBit/s' Elect. Lett. Vol.9 p34 1973

COURTENAY T.H. et.al. 'Active imaging with a TEA CO$_2$ laser' Infrared Phys. Vol.16 p95-102 1975

CHU T.S., HOGG D.C. 'Effects of precipitation on propagation at 0.63 3.5 and 10.6microns' Bell Sys. Tech. J. Vol.47 p732-59 1968


CUTRONA L.J. 'Synthetic aperture radar' in Radar Handbook

De CREMOUX B., LEIBA E. 'Free carrier absorption for
10micron modulation' Proc. IEEE Vol.57 p1674-5 1969

CRUICKSHANK J.M. 'Transversely excited atmospheric CO₂
Vol.18 No.3 p290-3 1979

DANITY J.C. 'Laser speckle and related phenomena' Topics
in Applied Physics Vol.9 Springer-Verlag Berlin 1975

DAVIS J.I. 'Consideration of atmospheric turbulence in

DULEY W.W. 'CO₂ Lasers - Effects and Applications'
Academic Press 1976

DUNPHY J.R., et. al. 'Nonlinear propagation through fog'

EARNshaw K.B., OWENS J.C. 'A dual wavelength optical
distance measuring instrument which corrects for air

FOWLER V.J, SCHLAFER J. 'A survey of laser beam
deflection techniques' Proc. IEEE Vol.54 No.10
p1437-44 1966

FORRESTER P.A., HULME K.F. 'Review - laser rangefinders'
FRIED D.L. 'Optical heterodyne detection of an atmospheric- 
ally distorted signal wavefront' Proc. IEEE Vol.55 
p57-66 1967

GOODWIN J.C. GARSIDE B.K. 'Measurements of spontaneous 
emission factor for injection lasers' IEEE J. Quant. 

HENSHEW P.D. et.al. 'Digital beam switch for agile beam 

HUANG C.-C. et.al. 'Comparison of GaAs and CdTe Crystals 
for High Frequency Intracavity Coupling Modulation of 

HULL D.R. FREEMAN N.J. 'Dynamic range measurements on 
streak cameras with picosecond resolution' 

HULL R.J. MARCUS S. 'A tactical 10.6 micron imaging radar' 
Proc. of the National Aerospace and Electronics Conf. 
NAECON 78 Dayton Ohio USA 16-18 May p662-668

HULME K.F., COLLINS B.S. et.al. 'A CO₂ laser rangefinder 
using heterodyne detection and chirp pulse compression' 

HUGHES A.J., PIKE E.J. 'Remote measurement of wind speed 
1973


KRAUS J.D. 'Antennas' Chapter1 McGraw-Hill 1950

KRUSE P.W. et al. 'Elements of infrared technology: generation transmission and detection' John Wiley 1962


LAAKMAN ELECTRO-OPTICS INC. California USA.


LLOYD J.M. 'Thermal imaging systems' Plenum Press 1975


MAMON G. et al. 'Pulsed GaAs laser terrain profiler' Applied Optics Vol.17 p868-77 1978


NORTON S.J. Internal Report University of Surrey


RACETTE G. 'Absorption edge modulator utilizing a p-n junction' Proc.IEEE (Correspondence) Vol.52 p716 1964


ROSS M. 'Laser receivers' John Wiley 1966


SCHAFER F.P. 'Dye Lasers' Spinger-Verlag 1979

SILVER S. 'Antenna theory and design' MIT Radiation Laboratory Series Vol.12 Chapter1 1949


STEPHENS S.W. 'Advanced design of Joule Thompson coolers for infrared detectors' Infrared Phys. Vol.8 p25-35 1968


THOMPSON G.H.B. 'Physics of semiconductor laser devices' John Wiley and Sons 1980


Van de HULST H.C. 'Light scattering by small particles' John Wiley and Sons, New York. 1957


WHITE A.D. 'Simultaneous gas maser action in the visible and infrared' Proc.IRE Vol.50 p2366 1962


# APPENDIX CONTENTS

<table>
<thead>
<tr>
<th>APPENDIX No.</th>
<th>PAGE No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 A Short Range Active Imager</td>
<td>173</td>
</tr>
<tr>
<td>3.1 Temporal Variations Within the Laser Beam</td>
<td>179</td>
</tr>
<tr>
<td>Fig.A3.1/1 Spatial/Temporal Beam Profile</td>
<td></td>
</tr>
<tr>
<td>Fig.A3.1/2 Spatial/Temporal Beam Profile</td>
<td></td>
</tr>
<tr>
<td>Fig.A3.1/3 Spatial/Temporal Beam Profile</td>
<td></td>
</tr>
<tr>
<td>3.2 Laser Diode Simulation Computer Program</td>
<td>184</td>
</tr>
<tr>
<td>3.3 Summary of Laser Diode Measurements</td>
<td>197</td>
</tr>
<tr>
<td>4.1 Terrain Mapper Slope Error Analysis</td>
<td>204</td>
</tr>
<tr>
<td>Fig.A4.1/1 Effect of Range Uncertainty</td>
<td></td>
</tr>
<tr>
<td>Fig.A4.1/2 Effect of Angle Uncertainty</td>
<td></td>
</tr>
<tr>
<td>4.2 Target Reflectivity Measurements</td>
<td>209</td>
</tr>
<tr>
<td>Fig.A4.2/1 The Measurement System</td>
<td></td>
</tr>
<tr>
<td>Fig.A4.2/2 Reflectivity Curves</td>
<td></td>
</tr>
<tr>
<td>4.3 Selecting a Laser Diode</td>
<td>216</td>
</tr>
<tr>
<td>Fig.A4.3/1 Transfer Characteristics for a Typical Family of Laser Diodes</td>
<td></td>
</tr>
<tr>
<td>4.4 Effects of Receiver Defocusing/Obscuration</td>
<td>219</td>
</tr>
<tr>
<td>Fig.A4.4/1 Generalised Optical Receiver</td>
<td></td>
</tr>
<tr>
<td>Fig.A4.4/2 Effect of Defocusing</td>
<td></td>
</tr>
<tr>
<td>Fig.A4.4/3 Transition Range v Receiver FOV</td>
<td></td>
</tr>
<tr>
<td>Fig.A4.4/4 Effect of Receiver Blockage</td>
<td></td>
</tr>
<tr>
<td>4.5 Terrain Mapper Circuit Diagrams</td>
<td>226</td>
</tr>
<tr>
<td>4.6 Terrain Mapper Command Codes</td>
<td>232</td>
</tr>
<tr>
<td>5.1 Terrain Mapper FHS Transfer</td>
<td>233</td>
</tr>
<tr>
<td>5.2 Terrain Mapper Control Program</td>
<td>234</td>
</tr>
</tbody>
</table>
APPENDIX 1.1

A Short Range Active Imaging System

Introduction

The early work covered by the present project included experiments to assess the merits of active imagers and the sort of performance they might achieve. A relatively simple imaging system was built up and used to generate the results depicted in the introduction, in Fig.1.1 and Fig.1.2. This Appendix describes that early system briefly.

The more sophisticated system described in the main text has drawn on the design experience of this system, in particular in that it uses the same laser source. The description given here, of the earlier system, is consequently kept brief; however a more complete description is available elsewhere (Norton 1980). The material given here should be sufficient to indicate the operational characteristics of the equipment.

The Hardware

A block diagram of the active imager is shown in Fig.A1.1/1. Housed within the receiver casing is a 15cm diameter receiving mirror, photodetector and preamplifier, transmitter output deflection mirror and optical filter. Attached to the side of the receiver casing is the semiconductor laser diode based transmitter module.
Fig.A1.1/1 A short range active imager
The optical section of the receiver includes an optical filter, a photodetector/preamplifier assembly positioned at the prime focus of a F/1.8 receiving mirror.

The optical filter is formed by a 15cm diameter 'Schott Glass' RG830 long wavelength cut-off filter and the response of the silicon photodiode, giving an overall bandpass response of approximately 210nm centred at 900nm. This filter also serves as a cover protecting the optical components from dust and contamination.

The photodiode used is a silicon avalanche device (Texas Instruments TIXL56) with an active area of $5 \times 10^{-4} \text{cm}^2$, (0.25mm dia.) and a gain bandwidth product of 80GHz.

The instantaneous field of view (IFOV) of the receiving optics is given by:

\[
\text{IFOV} = \frac{\text{detector diameter}}{\text{focal length of mirror}}
\]

which for a .25mm diameter detector and a focal length of 270mm gives a IFOV of approximately 0.9 milliradians. A low noise transimpedance preamplifier, with a transimpedance of 100kohms and a bandwidth of 40MHz is mounted directly behind the photodetector.

The output signal from the transimpedance amplifier is filtered by a Gaussian response network. This configuration, for a rectangular shaped pulse, differs by only 0.5dB from the ideal but non-realisable matched filter.
After filtering the signal (plus noise) is compared to a reference level so that the signal 'limits' at the comparator output. Range-gating is performed digitally by a D-type flip-flop. The width of the range-gate is determined by the clocking time of the flip-flop, which is typically a few nanoseconds, corresponding to a range of less than 1m.

The optical transceiver assembly is mounted on a sturdy platform and gearbox (Decca Radar type 151 aerial turning unit). Two output shafts are available from the gearbox section. The first is geared down by 180:1 and is used to drive the azimuth indicator circuit. This comprises of a ten turn potentiometer coupled to the gearbox shaft. The maximum angular coverage using this arrangement is +/- 10 degrees which is more than adequate for this application. The resolution is limited by the potentiometer to 0.1 milliradians.

The transceiver elevation angle can be varied by means of an adjusting screw located at the rear of the gearbox platform. A 32 level switchable amplitude modulated voltage, each level corresponding to a particular elevation angle (i.e. picture line), is used to drive the Y channel of the display. The image of the target is built up, line-by-line, on direct print photographic paper using a fibre-optic faceplate cathode ray tube recorder (Medelec FOR-4.2 recording oscilloscope).

An avalanche transistor based circuit was adopted for the laser driver. The generated current pulse is shown in Fig.A1.1/2, also shown is the optical pulse, measured using
a) Current (lower trace) and optical pulses with laser driven at maximum rating (current scale 2A/div.)

b) Current (lower trace) and optical pulses with laser driven just above threshold (current scale 1A/div.)

Fig.A1.1/2 Laser drive current and optical waveforms (time scale - 10ns/div.)
a p.i.n. photodiode of 0.5ns risetime (Hewlett Packard HP4220) and a 1.3ns risetime oscilloscope (Hewlett Packard HP1722A). Fig.A1.1/2b shows the output pulse when the laser diode is driven just above threshold with a 4.5A current pulse. Owing to the large divergence angle (20degrees) of the laser diode output it is necessary to collimate the beam. This is achieved by a f/1 moulded aspheric condenser lens. The low f number is required to ensure that all of the laser's output power is collected by the collimating lens. To avoid further obscuration of the receiving optics the maximum size of the on axis transmitter output mirror which can be incorporated is 25mm diameter. This requires that the collimating lens should have a focal length of 50mm or less. The lens used here has a focal length of 25mm and a diameter of 31.5mm.
Temporal Variations within the Laser Beam

Essentially the same measurement system was used as for the series of measurements described in Chapter 3, apart from the arrangement of the optical detector. The detector (active diameter 0.2mm) was mounted at a distance of 30mm from the emitting facet of the laser diode. The detector was moved vertically in increments of 0.5mm above and below the nominal centre of the laser emission pattern. Each step corresponded to an angle increment of approximately 1 degree. The position of the detector was measured using a high precision dial gauge.

Figs A3.1/1 and /2 show the results obtained from a 5.5A threshold laser driven with a 15A approximately half-sine shaped pulse of basewidth 16ns (obtained from the Power Technology pulser). The emitting facet was orientated normal (Fig. A3.1/1) and parallel (Fig.A3.1/2) the measurement plane. The narrower beam divergence angle in the plane normal to the junction is evident. Distinct temporal variations can be observed across the beam profile in both cases. In the plane parallel to the junction considerable variations in the leading edge 'spike' are present. The magnified plots of the beam central region (Figs.3.1/1(b)and /2(b)) show that very little differential time delay is present across the beam. The time axis
graduations are spaced at approximately 75ps.

Fig.A3.1/3 shows the same laser orientated parallel to the measurement plane and driven at 25A. The plot is similar in profile to the 15A response. The ratio of the intensity of the leading edge peak to the main pulse body has now, however reduced.
a) Full beam profile

b) Magnified view of beam centre (Time axis lines 78ps)

Fig. A3.1/1 Spatial/Temporal beam profile for 5.5A threshold laser driven with Power Technology pulser at 15A. Emitting facet orientated normal to measurement plane.
a) Full beam profile

b) Magnified view of beam centre (Time axis lines 78ps)

Fig. A3.1/2 Spatial/Temporal beam profile for 5.5A threshold laser driven with Power Technology pulser at 15A. Emitting facet orientated parallel to measurement plane.
a) Full beam profile

b) Magnified view of beam centre (Time axis lines 78ps)

Fig. A3.1/3 Spatial/Temporal beam profile for 5.5A threshold laser driven with Power Technology pulser at 25A.
APPENDIX 3.2

Laser Diode Simulation Program

General Description

The laser diode simulation program solves the coupled rate equations for the electron and photon densities and produces a graphical plot of the temporal behaviour of these quantities. The program is written in standard ANSI FORTRAN77 and is composed of a main program segment plus a number of self-contained sub-programs. This modular approach allows modifications and additional custom routines to be easily implemented within the framework of the original program.

The differential equations for the electron and photon densities both include terms containing the other variable. A solution is therefore computed by solving one equation over a short time interval using the previous solution to the coupled equation as a constant. The coupled equation is then solved in a similar manner. This procedure is repeated until the solution has been obtained over the required time scale.

Before the equations are solved routines are called to generate the current waveform and select the values for the various constants.

Total CPU time is dependent on the time scale and time increment selected, but is typically a few seconds.
Only small modifications are necessary to the program to enable automatic rerunning and incrementing of either the constants or some parameter of the pumping current. In this way characteristics of, say, drive current amplitude versus, say, optical pulsewidth or turn on delay can easily be generated.

A brief description of the programs routines is given below together with a listing of the program.

Program Subroutines

Name: DC
Called From: CURRN
Routines Called: None

Presents the electron concentration to a value determined by the bias current, BIASI, selected by the user. (Note: BIASI can only be set to a value less than the currently selected threshold current, THRESI.)

Name: CONS
Routines Called: None
Called From: MAIN

On entry this routine displays the current values of the constants in the rate equations. In addition the rise-time of the measurement system filter and whether the filter is active, is also displayed. Any of the displayed parameters can be assigned new values.
Name: CURRN
Routines Called: - DC
Called From: - MAIN

On entry the routine prompts for one of five time scales to be selected (0-2.5ns up to 0-40ns). A choice of three waveform generators, trapezoidal, half-sine and user defined are available.

Trapezoidal: - the rise and fall times, halfwidth and peak amplitude of the pulse can be defined.

Half Sine: - defined by peak amplitude and base duration.

User Defined: - any arbitrary pulseshape comprising of 800 data points resident in a file accessible by the program.

The current waveform, once generated is stored in an array named ACUR.

Name: FILTER
Routines Called: - None
Called From: - MAIN

This routine simulates the effect of the limited bandwidth of the optical detection system used to observe the laser output. A simple low pass filter (6dB/octave roll off) is implemented.

Name: GPLOT
Routines Called: - GINO LIBRARY
Called From: SPLIT

Plots 800 point arrays (i.e. AECON and APCON) on currently defined axes.

---

**Name:** LABEL

**Routines Called:** None

**Called From:** MAIN

Enables axis labels and graph title to be entered via the keyboard.

---

**Name:** NORM

**Routines Called:** None

**Called From:** MAIN

Normalize 800 point plotting array by a factor $\frac{YMAX}{SVAL}$

---

**Name:** PEAK

**Routines Called:** None

**Called From:** MAIN

Finds peak value of any 800 element array. Peak value is returned to main program in the variable MAX.

---

**Name:** PLABEL

**Routines Called:** GINO LIBRARY

**Called From:** SPLIT

Prints text entered from LABEL routine.

---

**Name:** PULSE
Routines Called :- PEAK
Called From :- MAIN
Finds halfwidth duration of any 800 element array. Also obtains the location of the first array element which has a value greater than 0.1 times the peak value. When APCON is passed to this routine this value corresponds to the laser turn on time delay.

Name : SPLOT
Routines Called :- GINO LIBRARY, GPLOT, LABEL, PLABEL
Called From :- MAIN
Generates scaled axes.

Name : STORE
Routines Called :- None
Called From :- MAIN
This routine stores a total of 800 values of both the electron (ECON) and photon (PCON) densities in arrays AECON and APCON respectively. (Note: The rate equations are always solved with a fixed time increment, TIMEI, irrespective of the selected time scale to preserve accuracy. On the 2.5ns range a minimum of 800 points is generated whereas on the 40ns range 12800 points are obtained. Since 800 points is more than adequate for graphical display STORE automatically sub-samples the data to produce plotting arrays of 800 points).
************* LASER DIODE SIMULATION PROGRAM **********

S.J. Norton
Department of Electronic and Electrical Eng.
University of Surrey,
GUILDFORD,
Surrey.

DIMENSION AECON(800),APCON(800),ACUR(800),X(800)
REAL L,MAX
COMMON/ARR/ AECON,APCON,X,PECON
COMMON/CONST/ ECON,PCON,C1,C2,C3,C4,C5,C6,BIASI,THRESI
CHARACTER ANS
INTEGER Y,Z,V
M=0
RT=600
V=0
Z=2
CSCALE=20
FLAG=1
PRINT*,','
SCALE=100
THRESI=5.5
D=.01
L=.04
W=.0002
E=1.6E-19
C3=.000000005
C4=5.E17
C5=.002
C6=3E-12
CALL CURRN(ACUR,X,M,ISAMP,TSCALE,AMPS)
SVAL2=75
CALL CONS(W,L,D,SCALE,FLAG,RT,Z)
TIMEI=.0000000025/800
C2=1/(D*L*W*E)
C1=1/((C2*THRESI*C3-C4)*C6)
PCON=0
ECON=0
CALL DC(ACUR)
DO 40 I=1,16400
   DO 30 Y=1,Z
      V=V+1
      C7=EXP(-((C1*PCON+1/C3)*TIMEI))
      ECON=ECON*C7+(C1*C4*PCON+C2*ACUR(J))*(1-C7)/(C1*PCON+1/C3)
      C8=EXP((C1*(ECON-C4)-1/C6)*TIMEI)
      PCON=PCON*C8+(1-C8)*C5*ECON/(C3*(1/C6-C1*(ECON-C

40 CONTINUE
I1=ISAMP
REM=MOD(V,I1)
IF (REM.EQ.0) CALL STORE(AECON,APCON,X,ECON,PCON,
,TSCALE,J,I)
     IF (J.EQ.800) GOTO 50
CONTINUE
CONTINUE
IF (FLAG .EQ. -1 ) CALL FILTER(APCON,TIMEI,ISAMP,Z,RT)
CALL PEAK(AECON,PECON)
CALL PEAK(APCON,PPCON)
SCALE=.75*PECON/PPCON
SVAL=100
CALL NORM(AECON,PECON,SVAL)
CALL NORM(APCON,PPCON,SVAL2)
M=0
J=1
V=0
CALL PULSE(APCON,WIDTH,DELAY)
PRINT*, 'PEAK OPTICAL O/P',PPCON
CALL SPLLOT(TSCALE)
P R IN T *,'PRESS Q TO QUIT'
C PRINT*,'PRESS ANY KEY TO RE-RUN'
READ(*,'(A)') ANS
IF (ANS.EQ.'Q') GOTO 80
GOTO 10
80 END
C *************** PARAMETER CHANGE ROUTINE ***************
SUBROUTINE CONS(W,L,D, SCALE,FLAG,RT,Z)
COMMON/CONST/ ECON, PCON, C1, C2, C3, C4, C5, C6, BIASI, THRESI
REAL L
INTEGER Z
CHARACTER KEY *6,OUT *3
10 IF (FLAG.EQ.-1) THEN
   OUT='IN'
ELSE
   OUT='OUT'
END IF
PRINT*, 'PARAMETERS VALUES ARE:-'
PRINT*, '1 THRESHOLD CURRENT (A)',THRESI
PRINT*, '2 ELECTRON RELAXATION TIME (ns)',C3
PRINT*, '3 PHOTON RELAXATION TIME (ps)',C6
PRINT*, '4 SPONTANEOUS EMISSION PROB.',C5
PRINT*, '5 LASER CAVITY DIMENSIONS',W,D,L
PRINT*, '6 OPTICAL SCALE FACTOR',SCALE
PRINT*, '7 BACKGROUND CONCENTRATION',C4
PRINT*, '8 MEASUREMENT FILTER ',OUT
PRINT*, '9 FILTER RT = ',RT
PRINT*, '10 Z FACTOR = ',Z
PRINT*, 'CHANGE PARAMETERS Y/N'
READ(*,'(A)') KEY
IF (KEY.EQ.'Y') GO TO 20
RETURN
PRINT*, 'ENTER PARAMETER No. (ENTER 0 TO FINISH)'
READ*, I
IF (I.EQ.1) READ*, THRESI
IF (I.EQ.2) READ*, C3
IF (I.EQ.3) READ*, C6
IF (I.EQ.4) READ*, C5
IF (I.EQ.5) READ*, W
IF (I.EQ.6) READ*, SCALE
IF (I.EQ.7) READ*, C4
IF (I.EQ.8) FLAG=FLAG*(-1)
IF (I.EQ.9) READ*, RT
IF (I.EQ.10) READ*, Z
IF (I.EQ.0) THEN
CALL PICCLE
GOTO 10
END IF
GOTO 20
END

CURRENT WAVEFORM GENERATOR

SUBROUTINE CURRN(ACUR, X, M, ISAMP, TSCALE, AMPS)
DIMENSION ACUR(80,0), X(800)
COMMON/CONST/ ECON, PCON, C1, C2, C3, C4, C5, C6, BIASI, THRESI
SAVE
CHARACTER ANS*1
IF (M.EQ.1.AND.IN.EQ.1) GOTO 30
IF (M.EQ.1.AND.IN.EQ.2) GOTO 90
IF (M.EQ.1.AND.IN.EQ.3) GOTO 150
PRINT*, 'SELECT TIMEBASE'
PRINT*, '0 ....... 2.5 ns'
PRINT*, '1 ....... 5.0 ns'
PRINT*, '2 ....... 10 ns'
PRINT*, '3 ....... 20 ns'
PRINT*, '4 ....... 40 ns'
READ*, ITBASE
TSCALE=2.5
IF (ITBASE.EQ.1) TSCALE=5
IF (ITBASE.EQ.2) TSCALE=10
IF (ITBASE.EQ.3) TSCALE=20
IF (ITBASE.EQ.4) TSCALE=40
ISAMP=2**ITBASE
PRINT*, 'THREE WAVEFORM GENERATORS ARE AVAILABLE'
PRINT*, '1 ....... TRAPEZOIDAL PULSE'
PRINT*, '2 ....... HALF SINUSIOD'
PRINT*, '3 ....... USER SUPPLIED'
PRINT*, 'PLEASE SELECT 1, 2, 3'
READ*, IN
IF (IN.EQ.1) GOTO 20
IF (IN.EQ.2) GOTO 80
IF (IN.EQ.3) GOTO 120
PRINT*, 'CURRENT PULSE GENERATOR'
PRINT*, 'PLEASE SPECIFY THE FOLLOWING PARAMETERS'
PRINT*, 'PEAK CURRENT AMPLITUDE (AMPS)'
READ*, AMPS
PRINT*, 'LEADING EDGE RISE TIME (10-90
READ*, RTIME
PRINT*, 'TRAILING EDGE FALL TIME (10-90
READ*, FTIME
PRINT*, 'PULSE WIDTH 50 POINTS'
READ*, PWIDTH
T1=RTIME/1.6+PWIDTH-FTIME/1.6+FTIME/.8
C
T1= REAL TIME DURATION OF PULSE BASE
T1N=800/TSCALE
C
T1N= NORMALISED (TO 20ns TIME BASE) DURATION
RTIMEN=RTIME/.8*T1N
FTIMEN=FTIME/.8*T1N
T2=(RTIME/1.6+PWIDTH-FTIME/1.6)*T1N
30 DO 40 I=1,RTIMEN
   ACUR(I)=I/RTIMEN*AMPS
40 CONTINUE
DO 50 I=RTIMEN,T2
   ACUR(I)=AMPS
50 CONTINUE
DO 60 I=T2,T2+FTIMEN
   ACUR(I)=AMPS/FTIMEN*(T2+FTIMEN-I)
60 CONTINUE
DO 70 I=T2+FTIMEN,800
   ACUR(I)=0
70 CONTINUE
75 PRINT*, 'D.C. BIAS'
READ*, BIASI
IF (BIASI.GT.THRESI) THEN
   PRINT*, 'BIAS CURRENT IN EXCESS OF THRESHOLD CURRENT'
   PRINT*, 'PLEASE RE-ENTER BIAS CURRENT'
GOTO75
ENDIF
RETURN
C
*** HALF SINUSIOD GENERATOR ***
80 PRINT*, 'HALF SINUSIOD WAVEFORM GENERATOR'
PRINT*, 'ENTER PEAK CURRENT (AMPS)'
READ*, AMPS
PRINT*, 'BASE DURATION (ns)'
READ*, TB
IM=TB*800/TSCALE
90 DO 100 I=1,IM
   ACUR(I)=AMPS*SIN(I*3.141593/IM)
   +100 CONTINUE
DO 110 I=IM,800
   ACUR(I)=0
110 CONTINUE
115 PRINT*, 'D.C. BIAS LEVEL'
READ*, BIASI
IF (BIASI.GT.THRESI) THEN
   PRINT*, 'BIAS CURRENT IN EXCESS OF THRESHOLD CURRENT'
   PRINT*, 'PLEASE RE-ENTER BIAS CURRENT'
GOTO115
ENDIF
RETURN
OPEN(3,FILE='USER')
READ(3,*) (ACUR(I),I=1,384,3)
DO 130 I=1,381,3
   ACUR(I+1) = (ACUR(I+3)-ACUR(I))/3 +ACUR(I)
   ACUR(I+2) = (ACUR(I+3)-ACUR(I))*2/3 +ACUR(I)
130 CONTINUE
PRINT*, 'PEAK CURRENT'
READ*, AMPS
DO 140 I=1,384
   ACUR(I) = ACUR(I)*AMPS
140 CONTINUE
150 PRINT*, ''
RETURN
END

**** DATA STORE ROUTINE ************
SUBROUTINE STORE(AECON,APCON,X,ECON,PCON,TSCALE,J,I)
DIMENSION APCON(800),AECON(800),X(800)
SAVE
J=J+1
AECON(J) = ECON
APCON(J) = PCON
X(J) = TSCALE*J/800
END

**** LOW PASS FILTER ************
SUBROUTINE FILTER(AFILT,TIMEI,ISAMP,Z,RT)
INTEGER Z
DIMENSION AFILT(800)
C = EXP(-TIMEI*Z*ISAMP/RT*2.2E12)
A = 0
DO 10 I=1,800
   A = A*C+AFILT(I)*(1-C)
   AFILT(I) = A
10 CONTINUE
END

***** FIND PEAK VALUE ************
SUBROUTINE PEAK(ARRAY,MAX)
REAL MAX
DIMENSION ARRAY(800)
MAX=0
DO 10 I=10,800
   IF (ARRAY(I).GT.MAX) MAX=ARRAY(I)
10 CONTINUE
END

******** FIND PULSEWIDTH ************
SUBROUTINE PULSE(ARRAY,WIDTH,DELAY)
DIMENSION ARRAY(800)
REAL MAX
CALL PEAK(ARRAY, MAX)
I = 1
10 IF (ARRAY(I).LT.0.1*MAX) DELAY = I
   IF (ARRAY(I).LT.MAX/2 .AND. ARRAY(I+1).GT.MAX/2) THEN
     P1 = I
     GOTO 20
   ELSE
     I = I + 1
   END IF
   GOTO 10
20 I = 1
30 IF (ARRAY(I).GT.MAX/2 .AND. ARRAY(I+1).LT.MAX/2) THEN
   P2 = I
   GOTO 40
ELSE
   I = I + 1
END IF
GOTO 30
40 WIDTH = P2 - P1
END
C
SUBROUTINE SPLIT(TSCALE)
DIMENSION AECON(800),APCON(800),XAR(800)
C
CHARACTER *40,XTEXT,YTEXT,TTEXT,TTEXT1,TTEXT2
DIMENSION IARR(10)
COMMON/STRING/XTEXT,YTEXT,TTEXT,TTEXT1,TTEXT2
COMMON/ARR/AECON,APCON,XAR,YMAX
CALL LABEL
I = 1
20 XMIN = 0
XMAX = TSCALE
YMIN = 0
XLX = XMAX/3
YMAX = 100
XLY = -YMAX/10
YLX = -XMAX/15
TLX = XMAX/3
TYL = YMAX
TLX1 = .75*YMAX
TLX2 = .7*YMAX
TLX3 = .6*XMAX
TLX4 = .6*XMAX
XLEN = 150
YLEN = 100
XOR = 20
XCON = XMAX/XLEN
YCON = YMAX/YLEN
CALL T4010
CALL PICCLE
CALL AXIPOS(1,XOR,XOR,XLEN,1)
CALL AXIPOS(1,XOR,XOR,YLEN,2)
CALL AXISCA(1,9,XMIN,XMAX,1)
CALL AXISCA(1,9,YMIN,YMAX,2)
CALL AXIDRA(10,1,1)
CALL AXIDRA(10,-1,2)
PRINT X LABEL

CALL CHASIZ(3.,3.)
CALL PLABEL(XTEXT,XLX,XLY)
PRINT Y LABEL

CALL CHAANG(90.)
CALL PLABEL(YTEXT,YLX,YLY)
PRINT GRAPH TITLE

CALL CHAANG(0.)
CALL PLABEL(TTEXT,TLX,TLY)
CALL GPlot(AECON,XAR)
CALL GPlot(APCON,XAR)
CALL DEVEND
END

*************** TEXT INPUT ROUTINE ***************

SUBROUTINE LABEL
CHARACTER*40 XTEXT,YTEXT,TTEXT,TTEXT1,TTEXT2
COMMON/STRING/XTEXT,YTEXT,TTEXT,TTEXT1,TTEXT2
DIMENSION IARRX(33),IARRY(33),IARRT(33)
PRINT*, 'X-AXIS LABEL'
READ(*, '(A)')XTEXT
PRINT*, 'INPUT Y-AXIS LABEL'
READ(*, '(A)')YTEXT
PRINT*, 'INPUT GRAPH TITLE'
READ(*, '(A)')TTEXT
END

*************** PRINT LABELS ***********************

SUBROUTINE PLABEL(TEXT,X,Y)
CHARACTER *40,TEXT

CALL GRAMOV(X,Y)
DO 10 I=1,INDEX(TEXT,'')-1
   CALL CHAASC(ICHAR(TEXT(I:I))-128)
10 CONTINUE
END

*************** GRAPH PLOT ***********************

SUBROUTINE GPlot(ARRAY,XAR)
DIMENSION ARRAY(800),XAR(800)
CALL GRAMOV(0.,0.)
DO 10 I=1,800
   CALL GRALINC(XAR(I),ARRAY(I))
10 CONTINUE
END

C  *************** NORM. DATA ***********************
SUBROUTINE NORM(ARRAY,YMAX,SVAL)
DIMENSION ARRAY(800)
DO 10 I=1,800
  ARRAY(I)=ARRAY(I)*SVAL/YMAX
10 CONTINUE
END

C  ************ B.C. BIAS ROUTINE *******************
SUBROUTINE DC(ACUR)
DIMENSION ACUR(800)
COMMON/CONST/ ECON,PCON,C1,C2,C3,C4,C5,C6,BIASI,THRESI
DO 10 I=1,800
  ACUR(I)=ACUR(I)+BIASI
10 CONTINUE
TIMEI=1E-10
DO 20 I=1,1000
  C7=EXP(-((C1*PCON+1/C3)*TIMEI))
  ECON=ECON*C7+(C1*C4*PCON+2*BIASI)*(1-C7)/(C1*PCON+1/C3)
  C8=EXP((C1*(ECON-C4)-1/C6)*TIMEI)
  PCON=PCON*C8+(1-C8)*C5*ECON/(C3*(1/C6-C1*(ECON-C4))
20 CONTINUE
PRINT*, 'ECON',ECON,'PCON',PCON,PCON
END
### APPENDIX 3.3

**Summary of Measured Laser Temporal Responses**

<table>
<thead>
<tr>
<th>Laser Type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITT 5.5A threshold laser</td>
<td>198,199</td>
</tr>
<tr>
<td>RCA 13.5A threshold laser</td>
<td>200,201</td>
</tr>
<tr>
<td>LDL 13A threshold laser</td>
<td>202</td>
</tr>
<tr>
<td>LDL 22A threshold laser</td>
<td>203</td>
</tr>
</tbody>
</table>

[Note: Both the pumping current pulse and optical pulse are shown in the following figures, in all cases the current pulse is the pulse which occurs first.]
Fig. A3.3/1 Measured Temporal Response of ITT Laser
Fig. A3.3/2 Measured Temporal Response of RCA Laser
Fig. A3.3/2 Cont.

[Graphs showing drive current and optical power over time]
Fig. A3.3/3 Measured Temporal Response of LD65 Laser
Fig.A3.3/4 Measured Temporal Response of LD67 Laser
APPENDIX 4.1

Slope Error Analysis for Terrain Mapper

The estimated local terrain slope will generally be in error owing to:

1) range uncertainty
2) angle pointing uncertainty

The situation is illustrated in Fig.A4.1/1 for the flat terrain case.

Range Uncertainty

Let $\partial r$ be the uncertainty in the range measurement. The corresponding worst case slope error, $\partial S_r$, caused by this range uncertainty is:

$$
\partial S_r = \frac{(R2 + \partial r) \sin(\phi + \Delta \phi) - (R1 - \partial r) \sin(\phi)}{(R1 - \partial r) \cos(\phi) - (R2 + \partial r) \cos(\phi + \Delta \phi)} \quad \text{(1)}
$$

For the flat terrain case we can eliminate $\phi$ since:

$$
\sin \phi = \frac{H}{R1} \quad \text{...... (2)}
$$

$$
\sin(\phi + \Delta \phi) = \frac{H}{R2} \quad \text{...... (3)}
$$
and
\[ \cos(\phi) = \sqrt{1 - \frac{H^2}{R_1^2}} \quad \ldots \quad (4) \]
\[ \cos(\phi + \Delta \phi) = \sqrt{1 - \frac{H^2}{R_2^2}} \quad \ldots \quad (5) \]
therefore
\[ \partial S_r = \frac{(R_2 + \partial r) H/R_2 - (R_1 - \partial r) H/R_1}{(R_1 - \partial r) \sqrt{1 - \frac{H^2}{R_1^2}} - (R_2 + \partial r) \sqrt{1 - \frac{H^2}{R_2^2}}} \quad \ldots \quad (6) \]
rearranging the numerator
\[ \partial S_r = \frac{\partial r H}{(R_1 - \partial r) \sqrt{1 - \frac{H^2}{R_1^2}} - (R_2 + \partial r) \sqrt{1 - \frac{H^2}{R_2^2}}} \quad \ldots \quad (7) \]

Tabulated values of slope error as a function of range uncertainty, for scanner heights of 1 and 2m are given in Tables A4.1.1 and 2.

Angle Pointing Uncertainty

The accuracy to which the laser beam can be directed will largely govern the slope error at longer ranges. With reference to Fig.A4.1/(b) we have :-

\[ R_2 = \frac{H}{\sin(\phi + \Delta \phi - \partial \phi)} \quad \ldots \quad (8) \]
\[ R_1 = \frac{H}{\sin(\phi + \partial \phi)} \quad \ldots \quad (9) \]
and the slope expression for the worst case slope error due to an pointing angle uncertainty, $\partial S\phi$, is:

$$
\partial S\phi = \frac{\sin(\phi + \Delta\phi)}{\sin(\phi + \Delta\phi - \partial\phi)} - \frac{\sin(\phi)}{\sin(\phi + \partial\phi)} \frac{\cos(\phi + \Delta\phi)}{\sin(\phi + \Delta\phi - \partial\phi)}
$$

Tabulated values of the slope uncertainty for a 1m sampling interval and scanner heights of 1m and 2m are given in Tables A4.1.3 and 4.

![Diagram](image)

a) Effect of range error

b) Effect of angle error

Fig. A4.1/1 Effects of measurement error on slope estimation.
<table>
<thead>
<tr>
<th>Scanner Height = 1M</th>
<th>Range (M)</th>
<th>Range Uncertainty - cms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>1.799</td>
<td>4.041</td>
</tr>
<tr>
<td>6</td>
<td>1.527</td>
<td>3.431</td>
</tr>
<tr>
<td>7</td>
<td>1.326</td>
<td>2.98</td>
</tr>
<tr>
<td>8</td>
<td>1.171</td>
<td>2.633</td>
</tr>
<tr>
<td>9</td>
<td>1.049</td>
<td>2.359</td>
</tr>
<tr>
<td>10</td>
<td>0.949</td>
<td>2.135</td>
</tr>
<tr>
<td>11</td>
<td>0.867</td>
<td>1.951</td>
</tr>
<tr>
<td>12</td>
<td>0.798</td>
<td>1.795</td>
</tr>
<tr>
<td>13</td>
<td>0.739</td>
<td>1.663</td>
</tr>
<tr>
<td>14</td>
<td>0.688</td>
<td>1.549</td>
</tr>
<tr>
<td>15</td>
<td>0.644</td>
<td>1.449</td>
</tr>
<tr>
<td>16</td>
<td>0.605</td>
<td>1.361</td>
</tr>
<tr>
<td>17</td>
<td>0.35</td>
<td>1.284</td>
</tr>
<tr>
<td>18</td>
<td>0.54</td>
<td>1.214</td>
</tr>
<tr>
<td>19</td>
<td>0.512</td>
<td>1.152</td>
</tr>
<tr>
<td>20</td>
<td>0.487</td>
<td>1.096</td>
</tr>
<tr>
<td>21</td>
<td>0.464</td>
<td>1.045</td>
</tr>
<tr>
<td>22</td>
<td>0.444</td>
<td>0.999</td>
</tr>
<tr>
<td>23</td>
<td>0.425</td>
<td>0.956</td>
</tr>
<tr>
<td>24</td>
<td>0.407</td>
<td>0.917</td>
</tr>
<tr>
<td>25</td>
<td>0.391</td>
<td>0.881</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scanner Height = 2M</th>
<th>Range (M)</th>
<th>Range Uncertainty - cms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>4.055</td>
<td>9.04</td>
</tr>
<tr>
<td>5</td>
<td>3.416</td>
<td>7.636</td>
</tr>
<tr>
<td>6</td>
<td>2.941</td>
<td>6.586</td>
</tr>
<tr>
<td>7</td>
<td>2.577</td>
<td>5.777</td>
</tr>
<tr>
<td>8</td>
<td>2.29</td>
<td>5.14</td>
</tr>
<tr>
<td>9</td>
<td>2.06</td>
<td>4.625</td>
</tr>
<tr>
<td>10</td>
<td>1.871</td>
<td>4.203</td>
</tr>
<tr>
<td>13</td>
<td>1.465</td>
<td>3.294</td>
</tr>
<tr>
<td>14</td>
<td>1.366</td>
<td>3.071</td>
</tr>
<tr>
<td>15</td>
<td>1.279</td>
<td>2.877</td>
</tr>
<tr>
<td>16</td>
<td>1.203</td>
<td>2.705</td>
</tr>
<tr>
<td>17</td>
<td>1.135</td>
<td>2.553</td>
</tr>
<tr>
<td>18</td>
<td>1.074</td>
<td>2.417</td>
</tr>
<tr>
<td>19</td>
<td>1.02</td>
<td>2.294</td>
</tr>
<tr>
<td>20</td>
<td>0.971</td>
<td>2.183</td>
</tr>
<tr>
<td>21</td>
<td>0.926</td>
<td>2.083</td>
</tr>
<tr>
<td>22</td>
<td>0.885</td>
<td>1.991</td>
</tr>
<tr>
<td>23</td>
<td>0.848</td>
<td>1.907</td>
</tr>
<tr>
<td>24</td>
<td>0.813</td>
<td>1.83</td>
</tr>
<tr>
<td>25</td>
<td>0.781</td>
<td>1.758</td>
</tr>
</tbody>
</table>

Table A4.1/1,2 Slope uncertainty (expressed in degrees from the horizontal) as a function of range uncertainty.
### Table 4.1/3, 4 Slope Uncertainty (expressed in degrees from the horizontal) as a function of pointing angle uncertainty.

#### Scanner Height = 1M

<table>
<thead>
<tr>
<th>Range</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>.29</td>
<td>.59</td>
<td>1.57</td>
<td>3.49</td>
<td>8.87</td>
</tr>
<tr>
<td>6</td>
<td>.34</td>
<td>.71</td>
<td>1.93</td>
<td>4.5</td>
<td>13.41</td>
</tr>
<tr>
<td>7</td>
<td>.4</td>
<td>.84</td>
<td>2.34</td>
<td>5.83</td>
<td>23.02</td>
</tr>
<tr>
<td>8</td>
<td>.46</td>
<td>.97</td>
<td>2.81</td>
<td>7.67</td>
<td>62.85</td>
</tr>
<tr>
<td>9</td>
<td>.52</td>
<td>1.11</td>
<td>3.37</td>
<td>10.48</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>.58</td>
<td>1.26</td>
<td>4.04</td>
<td>15.41</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>.65</td>
<td>1.42</td>
<td>4.89</td>
<td>26.69</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>.71</td>
<td>1.59</td>
<td>6</td>
<td>90.25</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>.79</td>
<td>1.79</td>
<td>7.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>.86</td>
<td>2</td>
<td>9.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>.94</td>
<td>2.25</td>
<td>13.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>1.02</td>
<td>2.52</td>
<td>21.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1.11</td>
<td>2.84</td>
<td>44.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>1.2</td>
<td>3.21</td>
<td>140.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1.31</td>
<td>3.66</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1.42</td>
<td>4.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>1.53</td>
<td>4.87</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>1.66</td>
<td>5.73</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>1.81</td>
<td>6.89</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>1.97</td>
<td>8.52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>2.14</td>
<td>11.01</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Scanner Height = 2M

<table>
<thead>
<tr>
<th>Range</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>.29</td>
<td>.58</td>
<td>1.5</td>
<td>3.15</td>
<td>6.99</td>
</tr>
<tr>
<td>6</td>
<td>.34</td>
<td>.69</td>
<td>1.81</td>
<td>3.87</td>
<td>9.03</td>
</tr>
<tr>
<td>7</td>
<td>.39</td>
<td>.81</td>
<td>2.13</td>
<td>4.69</td>
<td>11.71</td>
</tr>
<tr>
<td>8</td>
<td>.45</td>
<td>.92</td>
<td>2.48</td>
<td>5.63</td>
<td>15.46</td>
</tr>
<tr>
<td>9</td>
<td>.51</td>
<td>1.04</td>
<td>2.86</td>
<td>6.75</td>
<td>21.26</td>
</tr>
<tr>
<td>10</td>
<td>.56</td>
<td>1.17</td>
<td>3.27</td>
<td>8.1</td>
<td>31.76</td>
</tr>
<tr>
<td>11</td>
<td>.62</td>
<td>1.3</td>
<td>3.72</td>
<td>9.81</td>
<td>58.53</td>
</tr>
<tr>
<td>12</td>
<td>.68</td>
<td>1.43</td>
<td>4.23</td>
<td>12.05</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>.74</td>
<td>1.58</td>
<td>4.81</td>
<td>15.16</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>.8</td>
<td>1.72</td>
<td>5.47</td>
<td>19.82</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>.87</td>
<td>1.88</td>
<td>6.24</td>
<td>27.71</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>.93</td>
<td>2.05</td>
<td>7.16</td>
<td>44.56</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>2.22</td>
<td>8.27</td>
<td>119.81</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>1.07</td>
<td>2.41</td>
<td>9.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1.14</td>
<td>2.62</td>
<td>11.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1.22</td>
<td>2.84</td>
<td>13.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>1.3</td>
<td>3.08</td>
<td>17.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>1.38</td>
<td>3.34</td>
<td>22.77</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>1.46</td>
<td>3.62</td>
<td>32.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>1.55</td>
<td>3.94</td>
<td>56.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>1.64</td>
<td>4.29</td>
<td>417</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX 4.2

Target Reflectivity Measurements

Introduction.

A number of reflectivity versus aspect angle measurements have been undertaken so that an appreciation could be gained of the variations in the received signal strength, which would be caused by changes in target aspect angle. The measurements were performed using a cw laser diode operating at a slightly shorter wavelength (850nm) than the pulsed GaAs laser wavelength of 904nm. The use of a cw source allows the amplitude of the reflected signal to be more accurately determined than with the pulsed GaAs laser.

The Measurement System.

A block diagram of the target reflectivity system is given in Fig.A4.2/1. The operation of the system is controlled by a PET microcomputer. The transmitter source used is a cw semiconductor laser diode (Laser Diode Labs. type LCW10) of rated output power 7mW. To provide discrimination against ambient light level variations the laser is modulated at a nominal frequency of 2kHz. A lens is required to achieve a collimated beam, and in this case a microscope objective of focal length 16mm and numerical aperture (N.A.) 0.25 is used. The beam size at the target (laser collimated) is approximately 1sq.cm, an adjustment is
Fig. A4.2/1 Target reflectivity measurement system
also provided to enable a focused beam to be generated.

A portion of the backscattered power is collected by a 25mm diameter 40mm focal length lens, situated directly below the transmitter output aperture. The separation of the receiver and transmitter apertures results in only a 0.2 degree misalignment between the receiver and transmitter optical axes. The field-of-view of the receiving optics is 1.5 degrees which corresponds to an area coverage of 0.1m at the target. This enables the illuminated area to be moved about on target samples with macroscopic surface structure without having to realign the receiving optics. The photodetector is a silicon device (RCA 30809) having an active diameter of 8mm. A stop of 1mm gives the required field-of-view. A high gain low noise amplifier follows the detector. A high pass filter (1kHz) provides prefiltering to reduce the large contribution from the mains lighting. A phase sensitive detector acting as a 'lock in' amplifier provides a d.c. voltage output proportional to the incident optical power level. Adjustment of the P.S.D. integration time enables the bandwidth of the system to be set, bandwidths of typically 5-10 Hz are used. The D.C. output voltage is digitized and stored.

Azimuth rotation of the target sample is achieved by means of a stepper motor which gives a basic 1.8 degrees step interval.

For targets with a high specular component the dynamic range of the analogue-to-digital converter may be insufficient and so a facility has been incorporated for
optical attenuators to be inserted in front of the receiver aperture in such cases.

In operation, a reference surface (white spray painted aluminium) is placed in the target holder, normal to the incident beam, and a received level is recorded for calibration purposes. The reference target is then replaced by the material under test. The target is rotated, in steps of 1.8 degrees, up to an angle of 45 degrees to the target normal, the received signal strength being recorded at each step. The sample is then rotated back to the normal position, again with readings being taken at each step. A check is made between the two readings recorded at each step position and if within 5% the average of the two readings is formed.

Results

A selection of measured reflectivity curves for various materials is shown in Fig. A4.2/2. The dashed line shown on each plot is the signal level which would be received from a Lambertian scatter.

Materials with a pronounced gross surface structure, such as concrete, house brick, tree bark etc., tend to give a larger signal return, caused by favourably orientated surface facets, at high angles of incidence than would be expected from Lambert's cosine law.

The reflectivity of most of the materials decreased when tested wet, although the shape of the reflectivity curve remained essentially unchanged.
Fig. A4.2/2 Cont. Target reflectivities ($\lambda = 0.85 \, \mu m$)
Fig.A4.2/2 Target reflectivities $(\lambda = 0.85 \mu m)$
Gloss painted surfaces, even if of a dark colour, gave a very strong return at near normal incidence, with the signal level dropping very rapidly for aspect angles greater than a few degrees from normal.

For a typical rural terrain mapping environment it can be concluded that reflectivities will generally be in the region 0.15 (wet soil) \sim 0.8 (dry green foliage).
Manufacturers published data on pulsed semiconductor laser performance is normally quoted for a drive current duration of 200ns (the maximum permissible current pulse duration). This is considered to be essentially the steady state operating condition. When operating with the pulsewidths of interest here, i.e., less than 10ns, this data has to be interpreted with care.

With pulsewidths less than 200ns the mean power dissipation is reduced, and it is then possible to operate the laser with a peak current in excess of the quoted maximum drive current. The maximum peak current can be increased by a factor of:

\[
\frac{\sqrt{200}}{\sqrt{t_{pw}}}
\]

where \( t_{pw} \) = pulsewidth in nanoseconds

since the critical damage level, \( P_c \) (measured in watts per cm of emitting facet [Kressel]) varies as the square root of the pulsewidth. Since the effective maximum peak current rating of the device has now increased, devices with a
maximum current rating (@ 200ns) less than the intended peak drive current can now be considered. This has two important implications. Firstly, a device with a lower threshold current may be used resulting in less current being 'wasted' in driving the laser to threshold. Hence for a given drive current a greater output power may be achieved. Secondly, since a lower threshold laser has a shorter emitting facet a brighter source is obtained. As the area illuminated by the laser at the target is proportional to the dimensions of the emitting facet improved spatial resolution may also be achieved.

Consider an example. Fig.[A4.3/1] shows the optical power output versus drive current characteristic of a typical family of laser diodes (data taken from Laser Diodes Laboratories LD series). A laser is required to operate at a peak current of 30A and 10ns duration. From Fig.[A4.3/1] the LD62 device gives the highest output power at 30A drive current. The peak drive current for this device is 20A (@200ns pulse duration) and 88A at 10ns pulse duration, so it is well within its power rating at this pulse duration. If the device with a maximum peak current greater than 30A (@200ns duration) had been chosen (the LD65 device) then a source only 50% as bright would have been obtained.
Fig.A4.3/1 Transfer characteristic for a typical family of pulsed laser diodes.
APPENDIX 4.4

Effect of Receiver Defocusing and Obscuration

When operating at close range two effects, namely receiver defocusing and receiver obscuration must be given careful consideration.

Consider the generalised receiving arrangement shown in Fig.A4.4/1.

![Generalised optical receiver](image)

**Fig.A4.4/1** Generalised optical receiver

It will be assumed that the optics are lossless. A central obscuration is included to represent the blockage caused, for example, by a photodetector housing or transmitter output aperture. As will be shown this has a pronounced
effect on system performance at close ranges.

Firstly consider the situation without the central blockage. At this point a distinction must be drawn between the terms received and detected power. The received power \( P_r \) is defined here as the power intercepted by the receiving element, and the detected power \( P_d \) as that actually impinging on the detector. For target ranges greater than \( \frac{f.D}{p} \) the detected and received powers are equal (receiver focused). For ranges less than \( \frac{f.D}{p} \) it can be shown that

\[
P_d = P_r \left( \frac{p}{fD} \right)^2
\]

\( R < \frac{f.D}{p} \)

and defining a transition range, \( R_t \), as the range at which the detector collects all the received signal, that is

\[
R_t = \frac{fD}{p}
\]

Since the power intercepted by the collecting aperture will have a \( R^{-2} \) dependency, the detected power, \( P_d \), can be expressed as:

\[
P_d = \frac{P_r}{R_t^2}
\]

for \( R < R_t \)
where \( Pr' = Pr \cdot R_t^2 \) and is range independent up to \( R_t \).

Hence for ranges up to \( R_t \) the detected signal power is constant. \( R_t \) can also be related to the field-of-view and aperture diameter of the receiving optics:

\[
R_t = \frac{D}{\text{FOV}} \quad \text{......... (4)}
\]

A plot of normalised receiver sensitivity vs range is shown in Fig. A4.4/2. The transition range, \( R_t \), as a function of receiver field of view, for 150mm, 100mm, and 50mm diameter apertures, is shown in Fig. A4.4/3.

Any blockage of the receiver aperture will cast a shadow in the focal plane of the lens. When the receiver is focused the effect of any blockage is simply to reduce the detected signal by the ratio of the blockage area to the effective aperture area at the blockage plane. However, for ranges less than the transition range considerable reduction in the detected power can occur. The diameter of the shadow is given by:

\[
a = \frac{X \cdot f}{R} \quad \text{......... (5)}
\]

where \( X \) = the diameter of the obscuration.

For detector diameters less than the obscuration shadow diameter the detector is completely obscured and no received power will be detected. The minimum range at which
FIG. A4.4/2 Effect of defocusing on receiver sensitivity

Relative RX. Sensitivity

LOG 10

RANGE (M)

LOG 10

Focal length = 100mm
aperture diameter = 100mm

p = 5mm  p = 2mm  p = 1mm  p = 0.5mm  p = 0.2mm
FIG.AN.A/3 Transition range as a function of receiver field of view
signal power can be detected is given by:

\[ R_{\text{min}} = \frac{X.f}{P} \]  \hspace{1cm} (6)

At ranges greater than \( R_{\text{min}} \) and less than \( R_t \) the received power is given by:

\[ P_d = P_r \left[ \left( \frac{p.R}{D.f} \right)^2 - \left( \frac{X}{D} \right)^2 \right] \]  \hspace{1cm} (7)

\[ = P_{r'} \left[ \left( \frac{1}{R_t} \right)^2 - \left( \frac{X}{D.R} \right)^2 \right] \]  \hspace{1cm} (8)

for \( R_{\text{min}} < R < R_t \)

If the blockage is not in the plane of the lens then the detected power is further diminished and becomes:

\[ P_d = P_{r'} \left[ \left( \frac{1}{R_t} \right)^2 - \left[ \frac{X}{R.D} \cdot \frac{1}{1-c/f} \right]^2 \right] \]  \hspace{1cm} (9)

for \( R_{\text{min}} < R < R_t \)

where \( c \) is the displacement away from the lens plane towards the focal plane.

A plot of the normalised receiver sensitivity versus target range for a blockage size of 25mm situated in the plane of the lens is shown in Fig.A4.4/4.
FIG. A4.4/4 Combined effect of defocusing and blockage on receiver sensitivity

Focal length = 100 mm
Aperture diameter = 100 mm
Blockage diameter = 25 mm
APPENDIX 4.5

TERRAIN MAPPER CIRCUIT DIAGRAMS

Computer Interface .................................. 227
Timing Module ....................................... 228
Frame Formater ....................................... 229
Power Supply ........................................ 230
Stepper Motor Drivers ................................ 231
HALF STEP STEPPER MOTOR DRIVER
(ONE MOTOR)
## APPENDIX 4.6

### TERRAIN MAPPER COMMANDS

<table>
<thead>
<tr>
<th>ASCII Character</th>
<th>Terrain Mapper Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>@</td>
<td>Delimiter</td>
</tr>
<tr>
<td>A</td>
<td>Aux. port select</td>
</tr>
<tr>
<td>B</td>
<td>Start raster scan</td>
</tr>
<tr>
<td>C</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>Azimuth motor ON/OFF</td>
</tr>
<tr>
<td>E</td>
<td>Elevation motor ON/OFF</td>
</tr>
<tr>
<td>F</td>
<td>Azimuth motor CW/CWW</td>
</tr>
<tr>
<td>G</td>
<td>Elevation motor CW/CWW</td>
</tr>
<tr>
<td>H</td>
<td>Azimuth motor CLOCK</td>
</tr>
<tr>
<td>I</td>
<td>Elevation motor CLOCK</td>
</tr>
<tr>
<td>J</td>
<td>Serial data CLOCK</td>
</tr>
<tr>
<td>K</td>
<td>Serial data counter CLEAR</td>
</tr>
<tr>
<td>L</td>
<td>Load frame parameter N1</td>
</tr>
<tr>
<td>M</td>
<td>Load frame parameter N2</td>
</tr>
<tr>
<td>N</td>
<td>Load frame parameter N4</td>
</tr>
<tr>
<td>O</td>
<td>Load frame parameter N5</td>
</tr>
</tbody>
</table>
When operating in the 'burst pulse' mode, where several laser pulses are transmitted per beam pointing direction at a rate of 10kHz, the HP85 computer must be configured as an input buffer. This enables the computer to read in data at a rate of up to 20kHz. As two bytes are sent from the terrain mapper per range measurement data can arrive at the HP85 at rates of up to 20kHz.

At the end of the scan a character string variable of length (no. of range readings)*2 has been created. An 8 byte header is added to the data string and the composite string can now be stored on the HP85's integral cassette tape storage system. Storing the data as character variables enables a 8 fold reduction in tape storage space compared to storing the data as integer variables.

<table>
<thead>
<tr>
<th></th>
<th>FRAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ID</td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>NO. OF LINES</td>
</tr>
<tr>
<td>6</td>
<td>NO. OF SHOTS/PIXEL</td>
</tr>
<tr>
<td>7</td>
<td>NO. OF PIXELS/LINE</td>
</tr>
<tr>
<td>8</td>
<td>NO. OF STEPS/PIXEL</td>
</tr>
<tr>
<td>9</td>
<td>RANGE WORD</td>
</tr>
<tr>
<td>10</td>
<td>No. 1</td>
</tr>
<tr>
<td>11</td>
<td>RANGE WORD</td>
</tr>
<tr>
<td>12</td>
<td>No. 2</td>
</tr>
<tr>
<td>13</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>etc</td>
</tr>
</tbody>
</table>

FHS Data Storage Format
APPENDIX 5.2

Terrain Mapper Control Program
10 CLEAR
20 DIM A(200)
30 DIM Z$"TEST"
40 DIM SCAN "SCAN COMPLETE"
50 INPUT U$  
60 IF U$="T" THEN 240
70 CLEAR
80 DISP "STOP"
90 INPUT R$  
100 IF R$="H" THEN 120
110 CLEAR
120 DISP "FILENAME MUST BE FOUR CHARACTERS LONG"
130 GOTO 270
140 IF R$="N" THEN 100
150 IF R$="EN" THEN 40
160 IF R$="OR" THEN 60
170 OUTPUT 706 ;"GA"
180 FOR I=1 TO C*D
190 ENTER USING #,W  
200 DISP A(I)
210 NEXT I
220 GOSUB 1390
230 CLEAR
240 CREATE F(T,1,E*C*D*2+1)
250 ASSIGN #1 TO FT
260 PRINT#1,2T
270 ASSIGN #1 TO *
280 STOP
290 MOVE 1,0  
300 FOR I=1 TO C*D
310 PLOT I  
320 NEXT I
330 RETURN
340 720 DISP "FILENAME"
350 INPUT F(T)
360 IF LEN(F(T))<2 THEN 760
370 GOTO 720
380 CLEAR & DISP "FILENAME MUST BE FOUR CHARACTERS LONG"
390 GOTO 720
400 IF R$="N" THEN 100
410 IF R$="DN" THEN 120
420 OUTPUT 706 ;"GA"
430 FOR I=1 TO C*D  
440 ENTER USING #,W  
450 DISP A(I)
460 NEXT I
470 GOSUB 1390
480 CLEAR
490 DISP "SCANNING..."
500 OUTPUT 706 ;"GA"
510 FOR I=1 TO C*D  
520 ENTER USING #,W  
530 DISP A(I)
540 NEXT I
550 GOSUB 1390
560 CLEAR
570 DISP "DATA FILENAME"
580 INPUT F(T)
590 IF LEN(F(T))<4 THEN 760
600 GOTO 720
610 IF R$="N" THEN 100
620 GOTO 720
630 IF R$="EN" THEN 40
640 IF R$="OR" THEN 60
650 OUTPUT 706 ;"GA"
660 FOR I=1 TO C*D  
670 ENTER USING #,W  
680 DISP A(I)
690 NEXT I
700 CLEAR & DISP "SCAN COMPLETE"
710 DISP LEN(Z$)/2;"DATA POINTS RECORDED"