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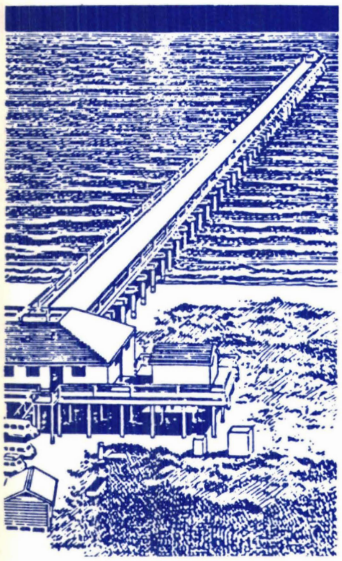

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HELICOPTER LIDAR BATHYMETER SYSTEM

Conceptual Design

by

Optech, Inc.
701 Petrolia Road
Downsview, Ontario, Canada M3J 2N6

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This report presents a technical evaluation of the likely performance of a Helicopter Lidar Bathymeter System (HLBS) that is being developed through an international agreement between the United States and Canada and is implemented through a joint Memorandum of Understanding under the US/Canadian Defense Development Sharing Program. Optech, Inc., is developing the HLBS, and the US Army Engineer Waterways Experiment Station is directing the overall development program.

The program is two-phased. Phase I, the development of a conceptual design, was initiated in March 1988 and completed in March 1989. Phase II provides for the detailed design, fabrication, and field testing of an operational prototype system. This report presents the conceptual design of the HLBS, which is designed for use from a Bell 212 helicopter at altitudes ranging from 100 to 1,000 m. The system is intended for use in water depths from approximately 1.5 to 35 m. Horizontal control will be provided

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either by microwave or the NAVSTAR Global Positioning System.

System components include an Nd:YAG laser transmitter/receiver with scanning device; an onboard system to acquire, initially process, and store all sensed data such as time, depth, and position; a system to provide the pilot with real-time navigation guidance; an aircraft attitude recorder for removing aircraft pitch and roll; a horizontal positioning system; and a status panel so the onboard operator can monitor system parameters and confirm that valid data are being collected. A ground-based system which postprocesses the collected data will produce as the final system product a fully corrected and quality-checked file of position and water depth referenced to standard survey control.

PREFACE

In an effort to modernize its hydrographic survey capabilities, the US Army Corps of Engineers has undertaken a joint development program with Canada to construct and field test an operational prototype airborne lidar bathymeter system. The first phase of the program, preparation of a detailed conceptual design, is complete, and the results are presented in this report. This report was prepared by Optech, Inc., Downsview, Ontario, Canada, through Contract No. DACW39-88-D-0039. Funding was provided by Headquarters, US Army Corps of Engineers (HQUSACE), Operations, Construction, and Readiness Division, and by the Department of Industry, Sciences, and Technology, Canada. The contract was monitored by the Coastal Engineering Research Center (CERC), US Army Engineer Waterways Experiment Station (WES).

The work reported was conducted by Optech, Inc., under the direction of Dr. John Banic, Project Manager, with contributions by Messrs. Sebastian Sizgoric, Don Carswell, Joe Liadsky, and Jacek Karezewski and Meses. Karen Francis and Elizabeth Carswell. Contract monitoring was provided by Mr. Thomas W. Richardson, Chief, Engineering Development Division (EDD), CERC, WES; Ms. Joan Pope, Chief, Coastal Structure and Evaluation Branch, EDD, and Mr. Jeff Lillycrop, EDD. General supervision for this study was provided by Dr. James R. Houston, Chief, CERC, and Mr. Charles C. Calhoun, Jr., Assistant Chief, CERC.

Program Technical Monitors during this investigation were Messrs. Mike Kidby, M. K. Miles, and Ted Pellicciotto of HQUSACE and Mr. Cliff G. Oldridge of the Department of Industry, Sciences, and Technology. Coordination with HQUSACE Civil Works Research and Developemnt was provided by Mr. Jesse Pfeiffer.

Technical review was provided by Drs. James K. Crossfield, California State University; James T. Kirby, University of Delaware; David R. Lyzenga, Environmental Reserach Institute of Michigan; Andrew B. Martinez, Tulane University; William D. Philpot, Cornell University; and Messrs. Gary C. Guenther, National Ocean Service; Kevin Logan, Engineering Topographic Laboratories; Gary Howell, CERC; and Kenneth G. Hall, Environmental Laboratory, WES.

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Commander and Director of WES during the publication of this report was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

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SECTION 1.0

INTRODUCTION

This report focuses primarily on the technical aspects of the proposed operational prototype Helicopter Lidar Bathymeter System (HLBS). It presents the HLBS conceptual design, the expected overall performance specification and the limits of its operational envelope. It assumes a certain familiarity with the relevant concepts of laser radar, light interaction with natural waters and similar matters.

The structure of the report is as follows: first, the system requirements, as defined by the U.S. Army Corps of Engineers (USACE), are outlined in Section 2, followed in Section 3 by a brief outline of the overall system concept intended to meet those requirements. Section 4 details the required design analyses and deals with parameter design trade-offs. The details of the proposed conceptual design are elaborated in Section 5 and form the bulk of the report. The evaluation and selection of the airborne platform and the preliminary mounting configuration for the system are discussed in Section 6. Factors relevant to the system installation and operation in the helicopter as regards the Federal Aviation Administration are discussed in Section 7. Finally, Section 8 provides a summary of the HLBS specifications and operational limitations. Further, a series of appendices contains the system training plan, documentation plan, diagnostic test plan, laboratory test plan and field test plan.

The design concepts for the HLBS are largely based on already proven techniques developed over the last two decades and built, by Optech, into several hardware systems. Best known of these, the LARSEN 500 system has produced survey data that is currently accepted by the Canadian Hydrographic Service for navigation chart production. The objective of the HLBS design efforts, which will feature some new capabilities, is a commercial lidar bathymeter system with performance that exceeds the best to date and meets the requirements of the USACE primarily, but also those of a broader hydrographic community. Although a number of trade-offs are required and a number of the final operating parameters can only be determined by testing the system in the field, the system proposed here represents a major step forward in shallow water hydrographic technology.

SECTION 2.0

SYSTEM REQUIREMENTS

2.1 General

The broad basis for the overall system requirements lies in the desire of the USACE to carry out its tasks in a more cost-effective manner. The USACE has long had a need for standard commercial instrumentation to conduct quick, accurate and economical bathymetric surveys of rivers, harbours, channels and coastal waterways. It conducts an extensive annual hydrographic surveying program in support of the planning, design, construction and maintenance of United States Federal water resource projects. Its surveying program includes both large-scale regional and site-specific missions, bathymetric and topographical localities, as well as a broad range of project types, including flood control, navigation and erosion control. The development of the HLBS is being proposed to provide the USACE with a practical system to augment boat-mounted acoustical surveying when their missions require rapid surveys.

The requirements that the HLBS must address fall into eight broad categories: airborne platform, survey mobilization/demobilization, system operation, depth capability, accuracy, sounding density, data processing and safety.

2.2 Airborne Platform

HLBS requirements for the airborne platform are as follows:

1. compatibility in weight, size and power demand with a medium-size standard commercial helicopter (eg. Bell 205 or 212)
2. no major modifications to the helicopter required by the HLBS installation
3. any helicopter modifications to be compatible with FAA regulations
4. instrument operation to be compatible with FAA regulations

2.3 Survey Mobilization/Demobilization

The target requirements for system installation are as follows:

1. modular construction
2. six hours installation time, including removal from shipping cases and any system calibration time
3. four hours removal and packing time
4. maximum of two qualified ground-based technicians necessary for installation or removal (with the possible exception of loading and unloading of heavier items)

2.4 System Operation

Operational aspects required are as follows:

1. a target of only one system operator, with a possibility of two (including a hydrographer in charge)
2. easy, maximally-automated control of system parameters
3. simple displays and monitors, visible under all operating conditions
4. sufficient monitoring of system performance parameters to ensure proper quality of data in acquisition

2.5 Depth Capability

2.5.1 Maximum Depth

The required maximum depth capability is that the system performance parameter Kd be greater than 3 in daytime and greater than 4 at night. As well, the system recording capability is to accomodate depths up to 40 m.

2.5.2 Minimum Depth

The target for minimum depth capability is 1 m under optimum environmental operating conditions. More typically, the minimum depth capability is expected to be in the 1-1.5 m range under all operating conditions.

2.6 Accuracy

2.6.1 Target Horizontal Accuracy

The target horizontal accuracy at the water surface, relative-to-aircraft, is ±0.5 m. The available aircraft positioning system will determine the absolute horizontal accuracy.

2.6.1.1 Positioning System

The aircraft will be positioned via one of the following:

1. Global Positioning System
2. microwave transponder system

The HLBS must incorporate one positioning system and be readily interfaced with the other.

2.6.2 Vertical Accuracy

1. Relative-to-water-surface: The nominal accuracy required in bottom location when referenced to the mean water surface is ±0.3 m (one sigma).
2. Relative-to-aircraft: The accuracy in bottom location when referenced to the aircraft will be somewhat degraded. The available aircraft positioning system will determine the absolute vertical accuracy.

2.7 Operational Modes

Two modes of operation are required: scanning and profiling. The scanning mode will generate a swath of soundings across the flight track. The profiling mode will keep a constant pointing orientation of the laser beam relative to the flight track.

2.8 Data Processing

The requirements for post-flight data processing are as follows:

1. automated reduction of the airborne data to an XYZ data file
2. software provisions for quality checking, smoothing and data editing to allow manual intervention in such processes on the part of the operator
3. provision for hard-copy output of a chosen data set
4. a target of 5:1 for the ratio of data-processing time to acquisition time

2.9 Safety

The main safety requirement is that the HLBS be eye-safe to the dark-adapted unaided human eye, in accordance with ANSI standards, from all operating altitudes. In addition, the aircraft pilot is to be able to override the system and shut off the laser.

SECTION 3.0

SYSTEM CONCEPT

3.1 Introduction

The system concept proposed to meet the USACE requirements outlined in the previous section is that of an airborne laser radar system or, more specifically, an airborne lidar bathymeter. The airborne scanning laser bathymeter represents a new generation in shallow-water hydrographic technology. It leaps as far beyond launch-acoustic techniques, which have dominated the field for 55 years, as acoustics did beyond the venerable lead line. A laser sounder is not, however, a replacement for sonar, but rather a complementary system, ideal for shoal areas (typically 1-30 meters depth, but as much as 50 meters in extremely clear waters). The payoffs can be a significant decrease in survey costs per unit area, increases in coverage rate and yearly area coverage, a rapid response reconnaissance capability, an improved spatial sounding distribution, and the ability to complete surveys rapidly in areas with small operational windows, such as Arctic regions.

An airborne lidar bathymeter can be thought of as an echo sounder which uses a beam of light rather than sound. It achieves a substantial advantage by operating at aircraft speeds rather than at ship speeds and by scanning across the flight path, thus covering a wide swath along each flight line.

3.2 Principle of Operation

Figure 3-1 illustrates the operating principle. A short pulse of infrared and a colinear short pulse of green laser radiation are simultaneously transmitted toward the water at an off-nadir angle θ. The infrared pulse is scattered from the water surface, while the green pulse penetrates the water and is scattered from the bottom as well. Scattering at both wavelengths is detected by a receiver at the aircraft, and the elapsed time between the scattering events is used to determine the water depth.

The relationships from which the depth, or the vertical coordinate, may be derived are outlined below.

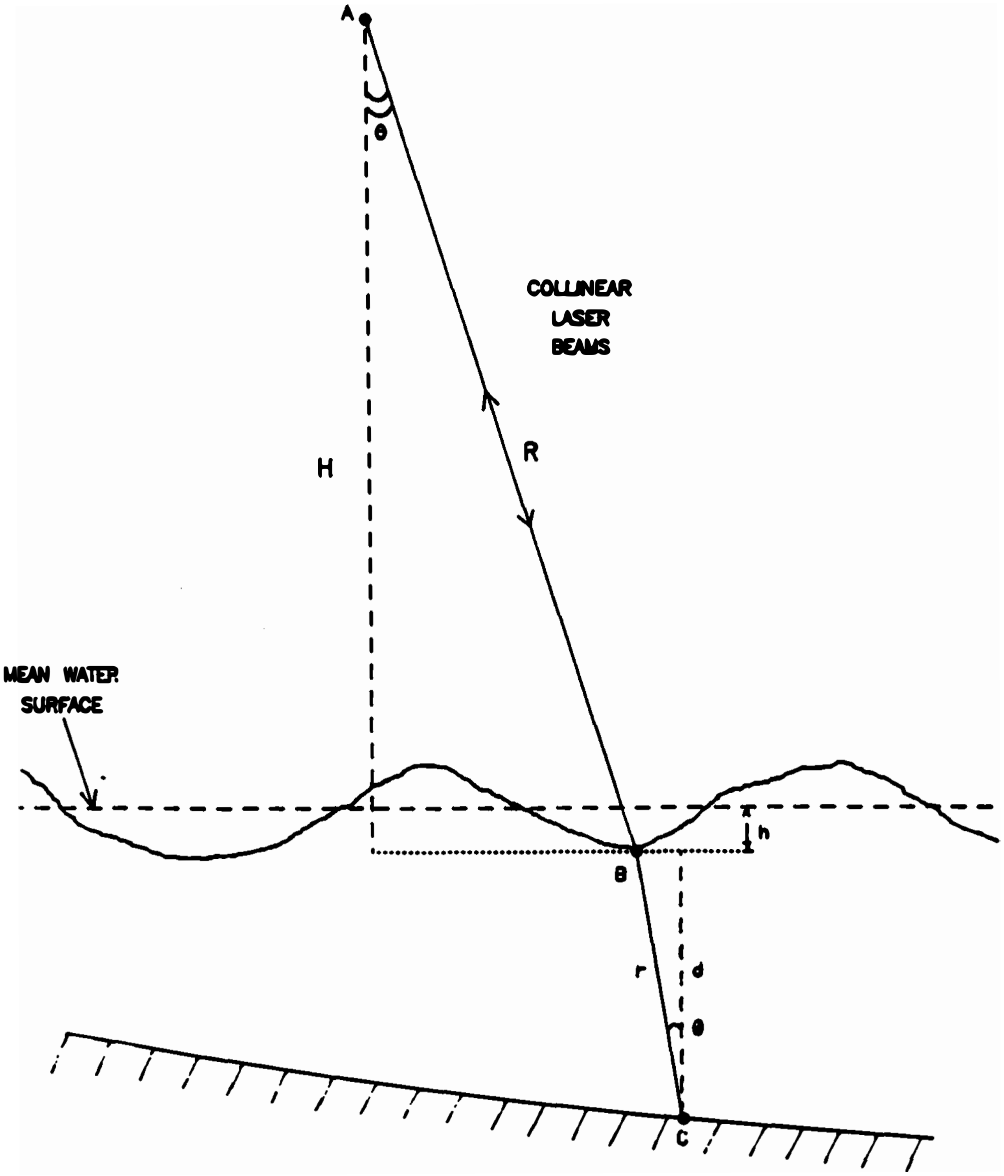

Figure 3-1. Operating principle

3.2.1 Depth

With reference to Fig. 3-1, the instantaneous depth value, d, at the point of measurement, C, is given by

$$d = r \cos\phi \qquad \text{Equation 3-1}$$

where $\sin \phi = \frac{\sin\theta}{n}$, and

n is the refractive index of water. r is a quantity measured by the system from the elapsed time between surface and bottom pulse scattering events. This instantaneous depth needs to be corrected for the wave height, h, and, eventually, for the tide level at that time. The former is derived from the lidar data while the latter is independently measured.

3.2.2 Vertical Co-ordinate: Submerged Topography

In the instance where it is desired to obtain the vertical co-ordinate of the bottom relative to the aircraft, the relationships are as follows:

$$H = R \cos \theta \qquad \text{Equation 3-2}$$

where R is the measured slant range from the aircraft, A, to the instantaneous water surface, B. The elevation of point C, relative to the aircraft, is

$$Z_{CA} = d + H \qquad \text{Equation 3-3}$$

where d and H are determined from Equations (3-1) and (3-2). If the elevation co-ordinate of the aircraft, Z_A, is accurately known from another measurement (e.g. a GPS positioning), then the required elevation co-ordinate of point C, Z_C, can be determined without involving the instantaneous water level parameters of waveheight and tide level through

$$Z_C = Z_A - Z_{CA} \qquad \text{Equation 3-4}$$

3.2.3 Vertical Coordinate: Dry Topography

This is a special case of that in Section 3.2.2, with $d = 0$.

3.3 System Description

A block schematic of the overall system is shown in Figure 3-2. The four major elements of the proposed HLBS system are the transceiver (TRS), data acquisition control and display (ACDS), aircraft positioning (APS) and ground-based data processing (DPS).

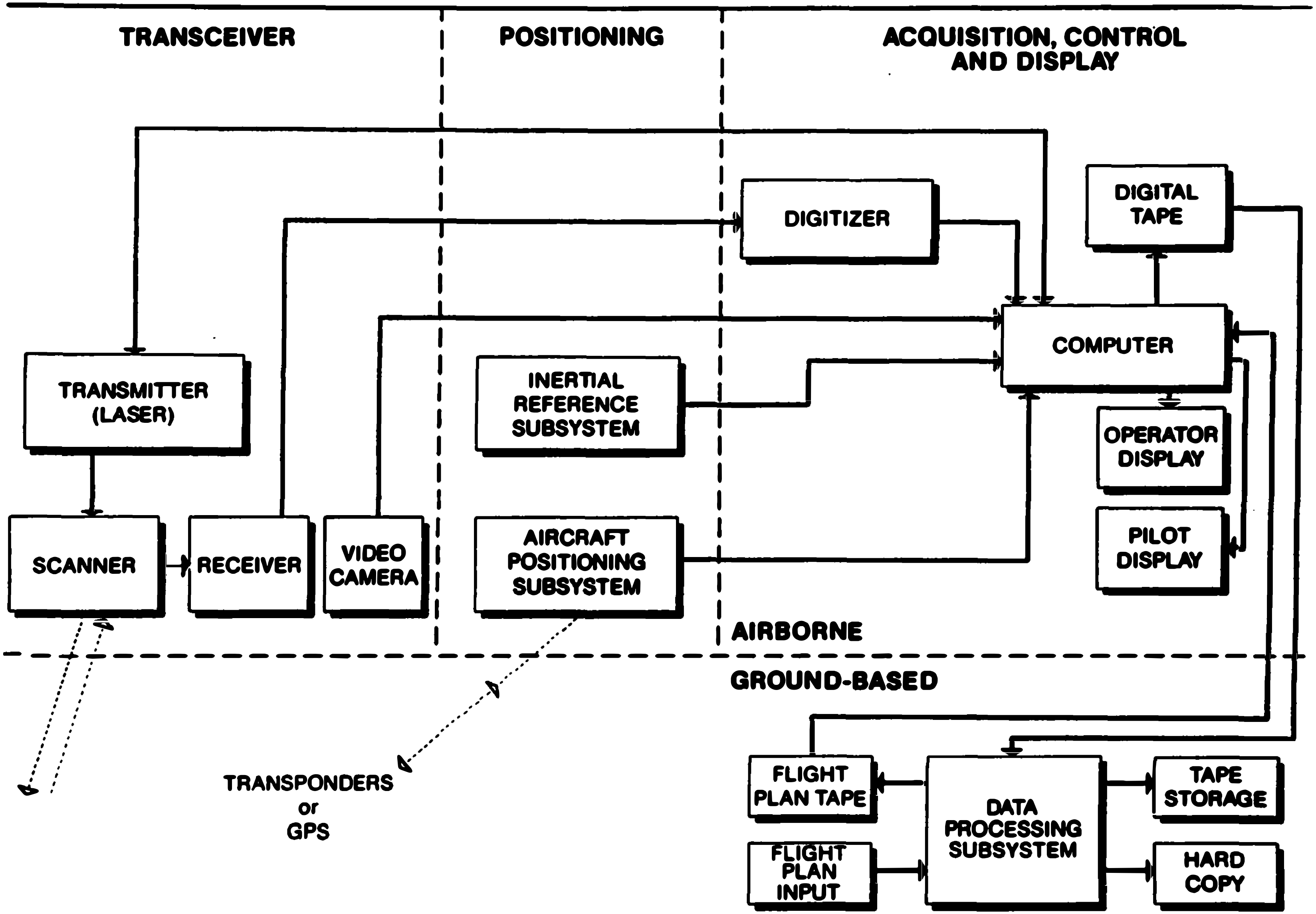

Figure 3-2. Block schematic

3.3.1 Transceiver Subsystem (TRS)

The main components of the TRS are:

1. laser subsystem, which provides the sounding radiation pulses
2. scanning subsystem, which provides the lateral movement of the sounding beam and its angular orientation relative to the sensor frame
3. receiver subsystem, which provides the collection, detection and electronic processing of the backscattered laser radiation
4. video camera/recorder, which provides a high-resolution video image of the sounded area
5. mounting subsystem, which provides both the structure necessary to hold and orient Items 1 through 4 and their interface to the aircraft

3.3.2 Acquisition, Control and Display Subsystem (ACDS)

The ACDS consists of the following major elements:

1. waveform digitizer, which captures the detected backscattered radiation signatures
2. digital tape recorder, which stores all data streams of interest
3. computer system, which provides the interfacing, processing and control function for all HLBS elements, and the time correlation for all stored data
4. operator display, which provides the system status monitoring, data quality monitoring and display functions
5. pilot display, which provides guidance information for flight management

3.3.3 Positioning Subsystem (APS)

The main elements of the APS are:

1. the aircraft positioning system receiver and antenna, which provide range information (or a co-ordinate location) with the time-correlation necessary for synchronization with other system data
2. the inertial reference subsystem, which provides the angular orientation of the transceiver

3.3.4 Data Processing Subsystem (DPS)

The DPS processes the airborne data to produce corrected depths, horizontal positions associated with each depth, and quality parameters associated with each XYZ data point. Its main components are:

1. data processing computer, with associated disc and tape storage
2. operator console/monitor, for display, quality control and editing
3. high-speed printer/plotter for generating hard-copy of selected data sets.

Details of the various hardware and software elements for the major system components outlined in the above sections are discussed in Section 5.

SECTION 4.0

SYSTEM ANALYSIS

This section discusses system design trade-offs, and addresses the critical issues involving system design, namely depth measurement errors, position measurement errors, signal-to-noise ratio, dynamic range, depth penetration capability, surface wave correction, minimum depth capability and eye safety.

4.1 System Design Trade-offs

The major system variables influence performance through numerous complex relationships, and are thus highly interdependent. The proper design of an airborne hydrographic lidar system requires a thorough understanding of these intricate relationships in order to determine acceptable operating ranges for each of the system variables. It is therefore necessary to examine carefully the many changes in system performance which can result from the alteration of a single variable, and to determine what other variables must be changed, in concert, in order to optimize the system's overall performance. For a comprehensive discussion of the interrelationships of the various system variables, the reader is referred to Guenther (1985)[1].

The two most important requirements that the system design must meet are depth measurement accuracy and depth penetration. The depth penetration capability of the system determines the surveyable area in which it can be used, and thus has a major impact on cost effectiveness. Other important design driving considerations are positioning accuracy, sounding density, coverage rate, eye safety, aircraft costs and environmental constraints. The following sections will discuss the important parameters, how they influence performance, and the acceptable operating range for each of these.

4.1.1 Scanner Nadir Angle

The scanner nadir angle and altitude determine the width of the swath and thus, for a given aircraft speed, the coverage rate. A scanner angle as large as possible is beneficial since coverage rate is one of the factors which strongly affects the cost/benefit ratio for the HLBS. However, depth measurement accuracy rapidly degrades with increasing nadir angle due to beam steering, propagation-induced biases, surface uncertainty, and geometric

[1] Guenther, C. G.,1985: Airborne Laser Hydrography: System Design and Performance Factors. NOAA Professional Paper Series, National Ocean Service 1, 385 pp.

effects. The optimum angle for minimization and correction of propagation-induced depth measurement bias errors is in the range of 15-25 degrees.

4.1.2 Aircraft Altitude

The flight altitude is selected to give the maximum swath width within bounds dictated by signal-to-noise ratio, desired sounding density and position accuracy. To produce the sounding density desired for the HLBS (typical 3-10 m spacing), and to meet the positioning accuracy requirement of ±50 cm (relative to the aircraft), the normal operating aircraft altitude will be 200 m. However, the system will be operational at altitudes up to 1000 m, but with degraded performance. The minimum operating altitude will be 100 meters.

4.1.3 Pulse Repetition Rate

The laser repetition rate is bound on the lower end by the sounding density required, and the minimum useful area coverage rate that would make the system cost beneficial. The upper end is determined by the maximum average power that the laser system can reliably produce, the maximum data rate the airborne data acquisition system can handle in real time, and the turnaround time needed to post-process a given amount of data. Taking all these factors into account, the optimum pulse repetition rate for the laser is in the 100-200 Hz range. The goal for the HLBS will be a 200-Hz laser system.

4.1.4 Transmitter Beam Divergence

Transmitter beam divergence has direct effects on penetration and accuracy, as well as on eye-safety limitations and the wave correction technique. Wave correction is best accomplished using a broader beam to average out the surface wave structure. Too broad a beam, however, will degrade the horizontal and vertical measurement accuracy of the system. In addition, if the system is to operate over a range of altitudes, the beam divergence must be made variable in order to keep the laser spot size on the surface relatively constant. On this basis, the HLBS divergence will be made variable in the range of 2-10 mrad, and a suitable divergence will be chosen for a given altitude.

4.1.5 Laser Pulse Energy

Maximum pulse energy is required in order to maximize depth penetration, which is an extremely important factor in the area coverage potential and cost-effectiveness of the system. The upper limit to the pulse energy is dictated by eye safety considerations and by size, weight and power restrictions on the laser ordained by the type of aircraft in which the system is installed. In addition, the gain in depth penetration beyond a pulse energy of 5-10 mJ is only marginal. Figure 4-1 shows the effect of laser pulse energy on depth penetration for nominal values of system and environmental parameters (see Section 4.4). Based on these considerations, the nominal laser pulse energy for the HLBS will be 5 mJ.

4.1.6 Laser Pulse Width

The laser pulse width should be as short as possible in order to maximize depth accuracy and increase the minimum depth capability of the system. The minimum pulse width readily achievable for a frequency-doubled Q-switched Nd:YAG laser is in the range of 5-10 ns. The goal for the HLBS will be a 5-ns pulse duration. There is little to be gained from a pulse duration much less than 5 ns, due to pulse stretching effects in the water column combined with the difficulty in achieving a receiver response fast enough to handle such a short pulse.

4.1.7 Receiver Field of View

The field-of-view required for optimum depth penetration is that value which is large enough, from the operational flight altitude, to encompass a diameter at the surface equal to approximately 70% of the water depth. Since the HLBS design is optimized for operation in water depths of less than 15 m, at an altitude of 200 m the largest receiver field of view required is approximately 50 mrad (0.7 x 15/200).

4.1.8 Receiver Optical Bandwidth

The optical bandwidth of the receiver should be as small as possible since the depth penetration of the system during daylight operation is limited by receiver shot noise, due to solar background radiation. The minimum bandwidth of the narrowband interference filter is limited by the system's relatively large field-of-view requirement, as well as by temperature effects. For the HLBS, the minimum optical bandwidth readily possible is approximately 1 nm. For nighttime operation the filter will be removed, thus eliminating its insertion loss and thereby improving the depth penetration capability of the system.

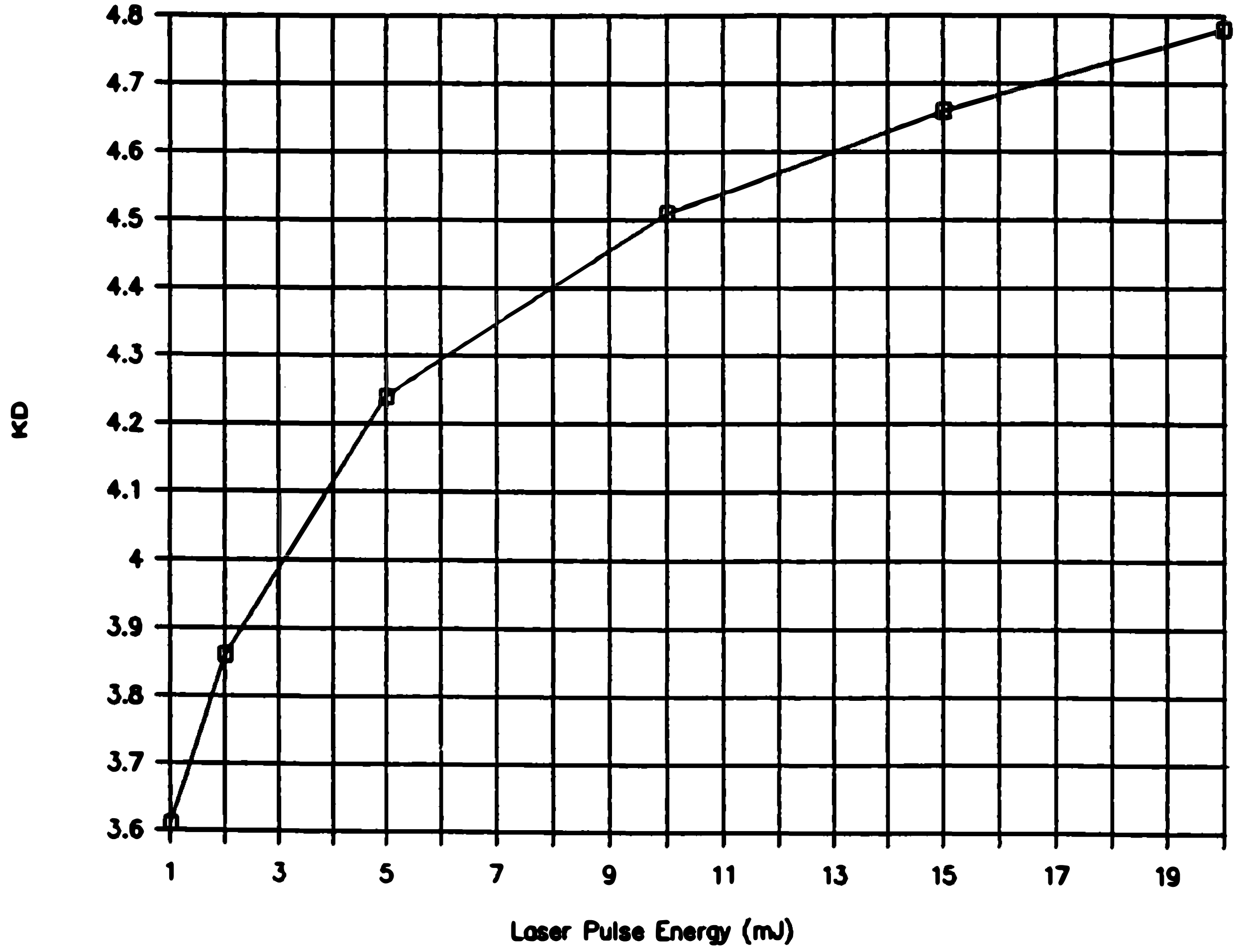

Figure 4-1. Effect of laser pulse energy on depth of penetration

4.1.9 Receiver Aperture

The telescope aperture should be as large as possible within the constraints of size and weight. This maximizes the signal-to-noise ratio, and thus the depth penetration. The effect of the receiver aperture on depth penetration, as determined from calculations using nominal system and environmental parameters (see Section 4.4), is shown in Figure 4-2. Above a diameter of approximately 20 cm, the gain in depth penetration is marginal; the HLBS receiver will therefore be designed with a 20-cm diameter aperture.

4.1.10 Receiver Temporal Resolution

The receiver response time must be sufficient to handle the narrow received optical pulses. This places a requirement on the electronic bandwidths of the photomultiplier (PMT) and avalanche photodiode (APD) detectors, the logarithmic amplifiers and the waveform digitizer. The anticipated overall risetime (10-90%) of the HLBS receiver, including the waveform digitizer, is approximately 4 ns.

The digitization interval of the digitizer must be short enough so that the analog signal from the photomultiplier/log amp can be digitized without significant degradation in temporal resolution. Similarly, the digital amplitude resolution of the waveform digitizer must be sufficient so as not to degrade the temporal resolution in the waveform. As analysis has shown that 8-bit amplitude resolution is not adequate, the HLBS digitizer will have a 1-ns digitization interval and 10-bit amplitude resolution.

4.2 Depth Measurement Error

4.2.1 Pulse Location Estimation

Depth measurement accuracy is highly dependent on the type of algorithm used to locate the surface and bottom return pulses in the lidar waveform. An analysis was performed to determine whether peak detection is sufficiently accurate to meet the requirements of the HLBS or whether a more sophisticated leading-edge detector would be required. The analysis estimated the effects of shot noise and system noise on the pulse location statistics for a peak detector, using waveforms obtained from the LARSEN 500 system.

The overall result of the analysis was a standard deviation of 2.7 ns for the peak of the bottom return signal. This corresponds to a random pulse estimation error of 30 cm. Random errors on the order of 30 cm are unacceptable, since that is the entire error budget for the system. It is clear that a peak detector will not supply sufficient accuracy. Leading-edge pulse location algorithms, which provide roughly one-third this random error, are required. For a discussion of leading-edge pulse location algorithms as applied to lidar waveforms, see Guenther (1988).[2,3]

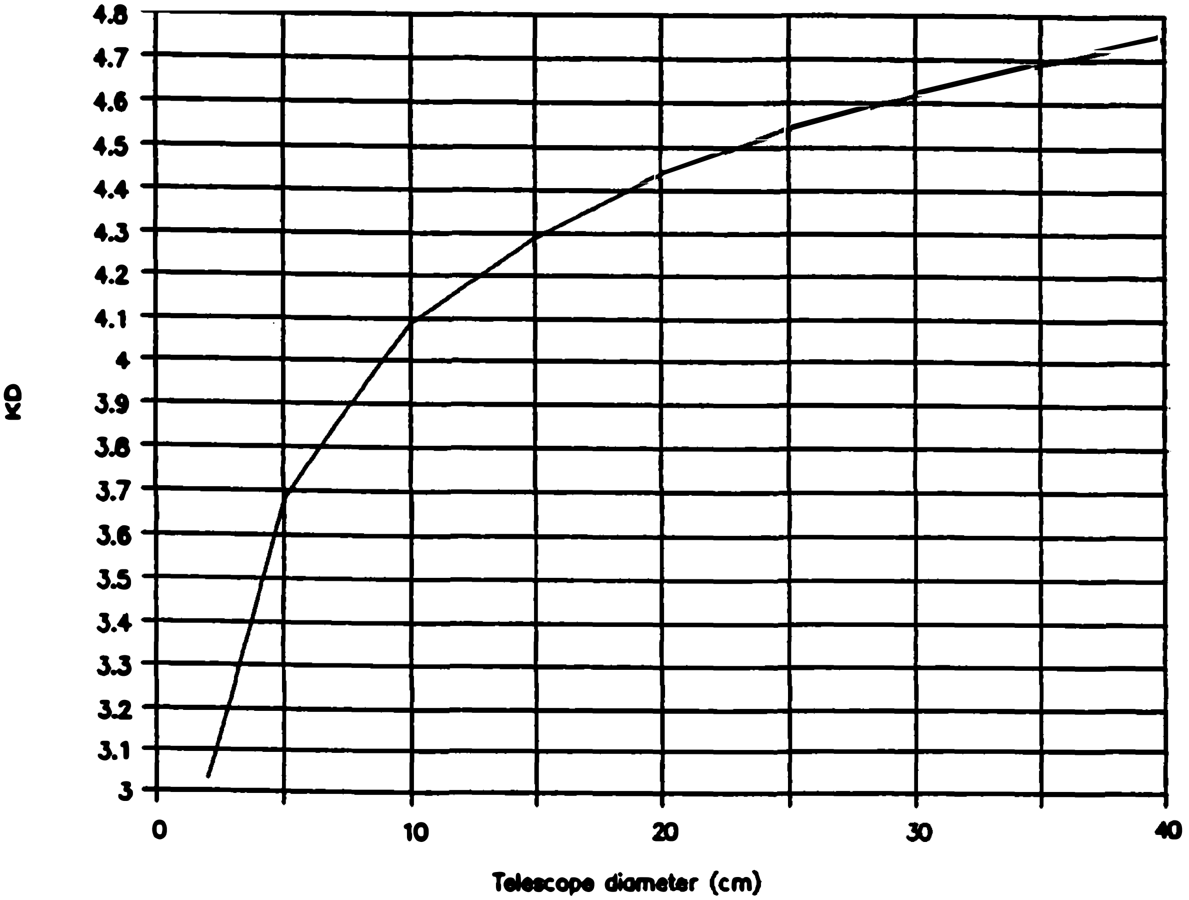

Figure 4-2. Effect of receiver aperture size on depth penetration

4.2.2 Effects of Nonlinear Processing

The nonlinear amplitude transfer characteristics of the logarithmic amplifier were studied to determine the effects of nonlinear processing on depth measurement accuracy.

The transfer function of the logarithmic amplifier was used to logarithmically transform a typical bottom return pulse, riding on a background level of volume backscattered laser energy and solar background noise. The output signal of the logarithmic amplifier was significantly distorted compared to the input signal. The desirable leading-edge pulse location algorithms applied directly to these distorted output waveforms would provide unreliable and inaccurate results. In view of the unacceptable accuracies associated with peak detection, it will be necessary to 'anti-log' the digitized waveform in software so that leading-edge pulse location algorithms can be utilized.

Different combinations of pulse and background amplitudes were used in the analysis to determine if the amplitude compression caused by the logarithmic amplifier, followed by the digitization process, leads to a loss of depth accuracy. With limited digitizer resolution, such compression might cause a permanent loss of resolution in the digitized signal, and an associated degradation in pulse location accuracy. The results of this analysis show that the random errors associated with digitizer truncation, for an 8-bit digitizer, for typical weak, stretched bottom returns, are no longer insignificant in their contribution to the overall error budget. A digitizer with an amplitude resolution of at least 10 bits will be used in the HLBS.

4.2.3 Water Surface Location

The infrared surface return signal will be used, when present, to locate the surface of the water accurately. When the infrared surface return signal is absent, the green return signal will be used. In the latter case, if the green return signal is produced by purely volumetric backscattering, a known bias correction will be applied to provide an accurate water surface location. Analysis shows that, for the hardware to be used in the HLBS, when no infrared signal is detected, the green return is almost purely from volumetric backscatter.

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2. G. C. Guenther, Analysis of Airborne Laser Hydrography Waveforms, Proceedings SPIE Ocean Optics IX, Vol. 925, April 4-7, 1988.

3. G.C. Guenther, Automated Lidar Waveform Processing, Proceedings of the Third Biennial National Ocean Service International Hydrographical Conference, Special Publication No. 21, April 12-15, 1988.

4.2.4 Depth Error Sources and Magnitudes

The subject of depth measurement errors has been addressed in detail in chapter nine of Guenther[1], and will not be repeated here. The purpose of this section is to summarize those results in tabular form for representative sets of operational parameters and to append some system hardware specific details. Tables 4-1 , 4-2, 4-3, 4-4 and 4-5 are provided to cover a range of depths of interest. Each table is broken down according to bias and random errors arising from hardware and environment factors, and concludes with a set of net results over a range of beam off-nadir angles. For this purpose, all errors are considered to be independent and thus add in quadrature as the root sum of squares (RSS).

Bias errors and random errors are distinguished by their temporal character. Bias errors depend primarily on slowly varying parameters and do not vary significantly for a series of shots. With modeling and the needed input parameters, bias errors can be predicted. Positive biases represent depths deeper than true, and negative biases are shoal. Random errors typically vary from shot to shot and are generally unpredictable. Some errors, such as surface origin uncertainty, may be manifest as either bias or random errors, depending, in this case, on surface wave statistics and the beam off-nadir angle.

It can be seen that a number of the raw bias errors are objectionably large and require correction in post-flight processing software. Error models have been developed, and algorithms exist for the calculation of bias predictions for use as bias correctors for these error sources. The expected residuals about these predictions are presented as the corrected error magnitudes. It should be noted that for water depths of less than two meters, the generally preferred leading-edge threshold pulse location algorithm becomes problematic and is replaced by a usually more noisy, but here better-suited peak detector. With the exception of this special case, the net bias and random errors are seen to increase with increasing depth. Note that for a 15-degree off-nadir beam angle, the net bias errors are larger than at 25 degrees, while the net random errors are smaller. This is fortuitous, as it keeps the net total error relatively flat over this operational regime, which is dictated by the need to minimize the variation in propagation-induced pulse stretching biases with unknown water clarity parameters.

As seen in the tables, the predominant bias error for all but very shoal depths is the propagation-induced pulse stretching error. The chief random errors are the environmental errors, with beam steering playing a more important role at greater depths, and pulse location and wave corrector residuals more important for shoal waters. Pulse location errors are larger for weaker returns, and the accuracy requirements will act to set a minimum acceptable signal strength for waveform processing.

Table 4-1

Depth Measurement Error, Depth < 2 Meters

BIAS ERRORS			RANDOM ERRORS (RMS)	
HARDWARE	(uncorrected)	(corrected)	**HARDWARE**	
IR surface marker calibration	±2 cm	±2 cm	Altimeter time interval counter	±2 cm
Electronic drift (aging) (# preclude with periodic calibration)	#	±1 cm	Altimeter CFD jitter (weak signal worst case)	±5 cm
Thermal effects	±1 cm	±1 cm		
PMT propagation delay uncertainty versus high voltage	±1 cm	±1 cm		
Log amp amplitude dependent delay (§ 20-point correction table)	±22 cm*	<0.5 cm§	Log amp delay corrector residual	<±1 cm
Digitizer quantization (weak signals only)	n/a	n/a		
[Optical center block (2 - 5 meter depths only)]	+5 cm‡	±1 cm		
Spurious responses (Design and operate to preclude)		0 cm		
{IR/green channel risetime differential}	{±11 cm}*	±1 cm		
ENVIRONMENT			**ENVIRONMENT**	
Surface return geometric stretching	+(5-10) cm*	±2 cm	Waveheight correction residuals	±10 cm
Surface origin uncertainty	-(50-80) cm*		Wave-induced beam steering (@10 knot wind; approximate)	
no K estimate:		±17 cm	15° off nadir:	<±1 cm
with K estimate:		±5 cm	25° off nadir:	±1 cm
Pulse location	-(5-10) cm‡	±2 cm	Pulse location	
Propagation-induced pulse stretching	-60 to +40 cm*		strong, unstretched:	±20 cm
residual to model:		±5 cm	weak, stretched:	n/a
residual to unknown parameters (25°-15°):		n/a		
NET RESULT (RSS) (25°-15°)			NET RESULT (RSS) (25°-15°)	
no K estimate:		±18 cm	strong pulse:	±23 cm
with K estimate:		± 8 cm	weak pulse:	n/a

Key: * - requires correction in software
‡ - correct in software as necessary
{} - may or may not exist

Table 4-2

Depth Measurement Error, Depth = 5 Meters

BIAS ERRORS			RANDOM ERRORS (RMS)	
HARDWARE	(uncorrected)	(corrected)	HARDWARE	
IR surface marker calibration	±2 cm	±2 cm	Altimeter time interval counter	±2 cm
Electronic drift (aging) (# preclude more with periodic calibration)	#	±1 cm	Altimeter CFD jitter (weak signal worst case)	±5 cm
Thermal effects	±1 cm	±1 cm		
PMT propagation delay uncertainty versus high voltage	±1 cm	±1 cm		
Log amp amplitude dependent delay (§ 20-point correction table)	±22 cm*	<0.5 cm§	Log amp delay corrector residual	<±1 cm
Digitizer quantization (weak signals only)	+3±3 cm‡	±3 cm		
[Optical center block (2 - 5 meter depths only)]	+5 cm‡	±1 cm		
Spurious responses (Design and operate to preclude)		0 cm		
{IR/green channel risetime differential}	{±11 cm}*	±1 cm		
ENVIRONMENT			ENVIRONMENT	
Surface return geometric stretching	+(5-10) cm*	±2 cm	Waveheight correction residuals	±10 cm
Surface origin uncertainty	-(50-80) cm*		Wave-induced beam steering (@10 knot wind; approximate)	
no K estimate:		±9 cm	15° off nadir:	±1 cm
with K estimate:		±5 cm	25° off nadir:	±3 cm
Pulse location	0 cm	±2 cm		
Propagation-induced pulse stretching	-60 to +40 cm*		Pulse location	
residual to model:		±5 cm	strong, unstretched:	±9 cm
residual to unknown parameters (25°-15°):		±(4-7) cm	weak, stretched:	n/a
NET RESULT (RSS) (25°-15°)			NET RESULT (RSS) (25°-15°)	
no K estimate:		±(12-13) cm	strong pulse:	±15 cm
with K estimate:		±(10-11) cm	weak pulse:	n/a

Key: * - requires correction in software
‡ - correct in software as necessary
{} - may or may not exist

Table 4-3

Depth Measurement Error, Depth = 10 Meters

BIAS ERRORS			RANDOM ERRORS (RMS)	
HARDWARE			**HARDWARE**	
	(uncorrected)	(corrected)		
IR surface marker calibration	±2 cm	±2 cm	Altimeter time interval counter	±2 cm
Electronic drift (aging) (# preclude more with periodic calibration)	#	±1 cm	Altimeter CFD jitter (weak signal worst case)	±5 cm
Thermal effects	±1 cm	±1 cm		
PMT propagation delay uncertainty versus high voltage	±1 cm	±1 cm		
Log amp amplitude dependent delay (§ 20-point correction table)	±22 cm*	<0.5 cm§	Log amp delay corrector residual	<±1 cm
Digitizer quantization (weak signals only)	+3±3 cm‡	±3 cm		
[Optical center block (2 - 5 meter depths only)]	n/a	n/a		
Spurious responses (Design and operate to preclude)		0 cm		
{IR/green channel risetime differential}	{±11 cm}*	±1 cm		
ENVIRONMENT			**ENVIRONMENT**	
Surface return geometric stretching	+(5-10) cm*	±2 cm	Waveheight correction residuals	±10 cm
Surface origin uncertainty	-(50-80) cm*		Wave-induced beam steering (@10 knot wind; approximate)	
no K estimate:		±9 cm	15° off nadir:	±3 cm
with K estimate:		±5 cm	25° off nadir:	±6 cm
Pulse location	+(4-10) cm‡	±2 cm	Pulse location	
Propagation-induced pulse stretching	-60 to +40 cm*		strong, unstretched:	±10 cm
residual to model:		±5 cm	weak, stretched:	±20 cm
residual to unknown parameters (25°-15°):		±(5-10) cm		
NET RESULT (RSS) (25°-15°)			**NET RESULT** (RSS) (25°-15°)	
no K estimate:		±(12-15) cm	strong pulse:	±(16-15) cm
with K estimate:		±(10-13) cm	weak pulse:	±(24-23) cm

Key: * - requires correction in software
‡ - correct in software as necessary
{} - may or may not exist

Table 4-4

Depth Measurement Error, Depth = 20 Meters

BIAS ERRORS	RANDOM ERRORS (RMS)
HARDWARE (uncorrected) (corrected) IR surface marker calibration ±2 cm ±2 cm Electronic drift (aging) (# preclude more with periodic calibration) # ±1 cm Thermal effects ±1 cm ±1 cm PMT propagation delay uncertainty versus high voltage ±1 cm ±1 cm Log amp amplitude dependent delay (§ 20-point correction table) ±22 cm* <0.5 cm§ Digitizer quantization (weak signals only) +3±3 cm‡ ±3 cm [Optical center block (2 - 5 meter depths only)] n/a n/a Spurious responses (Design and operate to preclude) 0 cm {IR/green channel risetime differential} {±11 cm}* ±1 cm	**HARDWARE** Altimeter time interval counter ±2 cm Altimeter CFD jitter (weak signal worst case) ±5 cm Log amp delay corrector residual <±1 cm
ENVIRONMENT Surface return geometric stretching +(5-10) cm* ±2 cm Surface origin uncertainty -(50-80) cm* no K estimate: ±9 cm with K estimate: ±5 cm Pulse location +(4-10)cm‡ ±2 cm Propagation-induced pulse stretching -60 to +40 cm* residual to model: ±5 cm residual to unknown parameters (25°-15°): ±(7-13) cm	**ENVIRONMENT** Waveheight correction residuals ±10 cm Wave-induced beam steering (@10 knot wind; approximate) 15° off nadir: ±5 cm 25° off nadir: ±13 cm Pulse location strong, unstretched: ±10 cm weak, stretched: ±20 cm
NET RESULT (RSS) (25°-15°) no K estimate: ±(13-17) cm with K estimate: ±(11-16) cm	**NET RESULT** (RSS) (25°-15°) strong pulse: ±(20-16) cm weak pulse: ±(26-24) cm

Key: * - requires correction in software
‡ - correct in software as necessary
{} - may or may not exist

Table 4-5

Depth Measurement Error, Depth = 30 Meters

BIAS ERRORS			RANDOM ERRORS (RMS)	
HARDWARE	(uncorrected)	(corrected)	**HARDWARE**	
IR surface marker calibration	±2 cm	±2 cm	Altimeter time interval counter	±2 cm
Electronic drift (aging) (# preclude more with periodic calibration)	#	±1 cm	Altimeter CFD jitter (weak signal worst case)	±5 cm
Thermal effects	±1 cm	±1 cm		
PMT propagation delay uncertainty versus high voltage	±1 cm	±1 cm		
Log amp amplitude dependent delay (§ 20-point correction table)	±22 cm*	<0.5 cm§	Log amp delay corrector residual	<±1 cm
Digitizer quantization (weak signals only)	+3±3 cm‡	±3 cm		
[Optical center block (2 - 5 meter depths only)]	n/a	n/a		
Spurious responses (Design and operate to preclude)		0 cm		
{IR/green channel risetime differential}	{±11 cm}*	±1 cm		
ENVIRONMENT			**ENVIRONMENT**	
Surface return geometric stretching	+(5-10) cm*	±2 cm	Waveheight correction residuals	±10 cm
Surface origin uncertainty	-(50-80) cm*		Wave-induced beam steering (@10 knot wind; approximate)	
no K estimate:		±9 cm	15° off nadir:	±8 cm
with K estimate:		±5 cm	25° off nadir:	±19 cm
Pulse location	+(4-10) cm‡	±2 cm	Pulse location	
Propagation-induced pulse stretching	-60 to +40 cm*		strong, unstretched:	±10 cm
residual to model:		±5 cm	weak, stretched:	±20 cm
residual to unknown parameters (25°-15°):		±(9-15) cm		
NET RESULT (RSS) (25°-15°)			NET RESULT (RSS) (25°-15°)	
no K estimate:		±(15-19) cm	strong pulse:	±(24-17) cm
with K estimate:		±(12-17) cm	weak pulse:	±(30-24) cm

Key: * - requires correction in software
‡ - correct in software as necessary
{} - may or may not exist

4.3 Position Measurement Error

The horizontal measurement accuracy of the system depends on several factors which can contribute to the overall error. The error sources include the scanner angle encoder, the attitude and altitude measurement systems, the positioning system, laser scan angle calibration techniques, transmitter/receiver optical alignment, and calibration of the relative positions of the lidar sensor and positioning-system receiver. The accuracies of these systems are summarized in Table 4-6. The RMS error (E_R) in the position of a laser spot on the surface, relative to the aircraft, is given by

$$E_R = \sqrt{(SAE^2+SCX^2+SCY^2+SCO^2+TRA^2+AR^2+AP^2+AA^2+A^2+ASC^2)}$$

Equation 4-1

where the values for the parameters in parentheses are the error contributions at an altitude of 200 m.

This yields a value of $E_R = 50$ cm. Note that most of these random errors are angular, and therefore altitude-dependent. To a good approximation, the RMS horizontal error in the surface spot relative to the horizontal position of the aircraft is 25 cm per 100 m of aircraft altitude.

The absolute location error of the surface spot is given by the expression

$$E_S = \sqrt{(E_R^2 + E_A^2)}$$

Equation 4-2

where E_A is the uncertainty in the absolute position of the aircraft. For nominal values of $E_R = 0.5$ m and $E_A = 2$ m, the surface spot location accuracy is $E_S = 2.1$ m. Note that this error is due mainly to the absolute position of the aircraft.

An additional horizontal error in the location of the spot on the bottom, relative to the water surface, is approximately 0.04d, where d is the water depth (this information is deduced from analyses contained in "Airborne Laser Hydrography" by G. Guenther, March 1985). For a nominal 15-m depth, this adds an additional bias error of $E_B = 60$ cm to the horizontal co-ordinate relative to the aircraft.

The absolute accuracy in the bottom location is a combination of the absolute random error of $E_S = 2.1$ m and the horizontal bias error of $E_B = 0.6$ m.

Table 4-6

Horizontal Absolute Position Measurement Errors

Error Source		Accuracy	Effect at 200 m
Scan angle encoder	(SAE)	0.02 deg	2 cm
Scan calibration - x	(SCX)	0.03 deg	10 cm
- y	(SCY)	0.03 deg	10 cm
- θ	(SCO)	0.1 deg	10 cm
Transmitter/Receiver Alignment	(TRA)	0.02 deg	7 cm
Attitude - roll	(AR)	0.05 deg	17 cm
- pitch	(AP)	0.05 deg	17 cm
- azimuth	(AA)	0.4 deg	34 cm
Altitude	(A)	0.2 m	5 cm
Aircraft/Sensor Calibration	(ASC)	0.1 m	10 cm

4.4 Signal-To-Noise and Dynamic Range Calculations

The equations and assumptions made in calculating the signal-to-noise ratio (S/N) will determine the maximum water depth that the system is capable of measuring, as well as the expected signal levels. The latter is an important consideration in system design, since too large a signal will result in saturation of the detectors or other undesirable results. The PMT, for instance, suffers from afterpulsing when it is exposed to too high an optical input.

The green signal return is detected by a PMT channel and an APD channel. Signal-to-noise ratios are calculated for both channels.

4.4.1 Signal-to-Noise Equations

The signal strength received from bottom reflections is given by Equation 4-3.

Received Signal Power:

$$P_R = \frac{E}{t_w} \; \eta_T \; \eta_R \; \frac{\rho F A \; e^{-2nkr} \; e^{-2\alpha R}}{\pi(n_w R + r)^2} \qquad \text{Equation 4-3}$$

Received Background Power:

$$P_B = S_\lambda \; \Delta\lambda \; \frac{\pi}{4} \; \theta_R^2 \; \frac{\pi D^2}{4} \; \eta_R \qquad \text{Equation 4-4}$$

where:

E = laser energy per pulse

t_w = laser pulse width (FWHM)

η_T = efficiency of transmitter optics

η_R = efficiency of receiver optics

ρ = reflectance of target (bottom)

F = beam overlap coefficient

A = area (aperture) of receiver telescope = $\frac{\pi D^2}{4}$
where D = aperture diameter

n = empirical excess loss factor

k = diffuse attenuation coefficient of water

α = atmospheric attenuation coefficient

S_λ = upwelling solar radiance scattered from water

n_w = refractive index of water

$\Delta\lambda$ = filter bandwidth

θ_R = receiver field of view (radians)

R = slant range in air (from transceiver to water surface).
R is related to the altitude, H, by: $H = R \cos\theta$, where θ is the beam entrance angle.

r = slant range in water (from water surface to bottom).
r is related to water depth, d, by: $d = r \cos\phi$, where ϕ is obtained from Snell's law applied to the refraction at the water surface. $\sin\theta = n_w \sin\phi$

The signal and background currents (before detector gain) are calculated by multiplying the respective calculated signal powers by the detector response (q):

$$I_s = q\ P_R \qquad \text{Equation 4-5}$$

$$I_b = q\ P_B \qquad \text{Equation 4-6}$$

In the case of the PMT the signal-to-noise ratio is calculated from:

$$S/N = \left[\frac{I_s^2\ G^2}{(\pi/2)B\ (2e\ (I_s + I_b)\ G^2 + I_{na}^2)}\right]^{1/2} \qquad \text{Equation 4-7}$$

where B = signal electronic bandwidth (noise bandwidth is (π/2)B)

e = electronic charge = 1.6×10^{-19} C

I_{na} = equivalent input noise current per √Hz of the amplifier

G = detector gain

For the APD the signal-to-noise ratio is calculated from:

$$S/N = \left[\frac{I_s^2\ G^2}{(\pi/2)B\ (2e\ (I_s + I_b)\ G^{2.3} + I_{nd}^2 + I_{na}^2)}\right]^{1/2} \qquad \text{Equation 4-8}$$

where I_{nd} = noise current per √Hz of the APD

4.4.2 S/N Calculations For The PMT Channel

If we assume that the minimum usable signal-to-noise ratio is 3, then for clear water ($k = 0.1\ \text{m}^{-1}$) and other parameters listed in Table 4-7, the maximum measurable depth by the PMT, during daytime, will be 37.1 m. Under these conditions, the output signal current will be 3.4 μA.

Table 4-7
S/N Calculations For PMT Channel

TRANSMITTER		**DETECTOR**	
Pulse Energy (mJ):	5	Responsivity (A/W):	0.04
Pulse Duration (ns):	5	Gain:	2000
Optical Efficiency:	0.9	Amplifier Noise (pA/√Hz):	50
		Bandwidth (MHz):	150
RECEIVER		**ENVIRONMENTAL**	
Diameter (cm):	20	Aircraft Altitude (m):	200
Field-Of-View (mrad):	50	Dif. Attn. Coef. (m^{-1}):	0.1
Filter Bandwidth(A):	10	Bottom Reflectivity:	0.1
Optical Efficiency:	0.135	FOV Loss Factor:	0.5
		Water Depth (m):	37.1
		Ambient Rad ($W/m^2/sr/\mu m$):	2
		Beam Entrance Angle (°):	15
		Atm. Atten. Coeff.(km^{-1}):	0.3
		Signal/Noise:	3.0
CALCULATIONS			
Signal Power (W):	4.3×10^{-8}		
Signal Current (A):	3.4×10^{-6}		
Background Power (W):	1.7×10^{-8}		
Background Current (A):	1.3×10^{-6}		
Noise Current (A):	1.1×10^{-6}		

In these calculations, the value of 0.135 for the optical efficiency of the receiver includes a factor 0.3 for the polarizer and a factor 0.9 to account for 10% of the signal being diverted to the other detectors. The FOV loss factor was set to 0.5.

Figure 4-3 shows the maximum water depth (for a S/N of 3) that can be measured as a function of the diffuse attenuation coefficient, k. Also included on the x-axis, for reference only, are the approximate values of the beam attenuation coefficient and the Secchi depth (based on a single scattering albedo of ~ 0.8). The curve shows that the depth capability of the system will be approximately equal to twice the Secchi depth.

In the above calculations, the reflection losses incurred at the surface of the water (about 2%) are ignored.

Setting $d = 0$ and $\rho = 0.2$, to get an estimate of the maximum PMT current, gives $I = 110$ mA. If we assume that the central block will attenuate the signal by a factor of 30 then we can expect a peak current of $\frac{110}{30} = 3.7$ mA, which is acceptable.

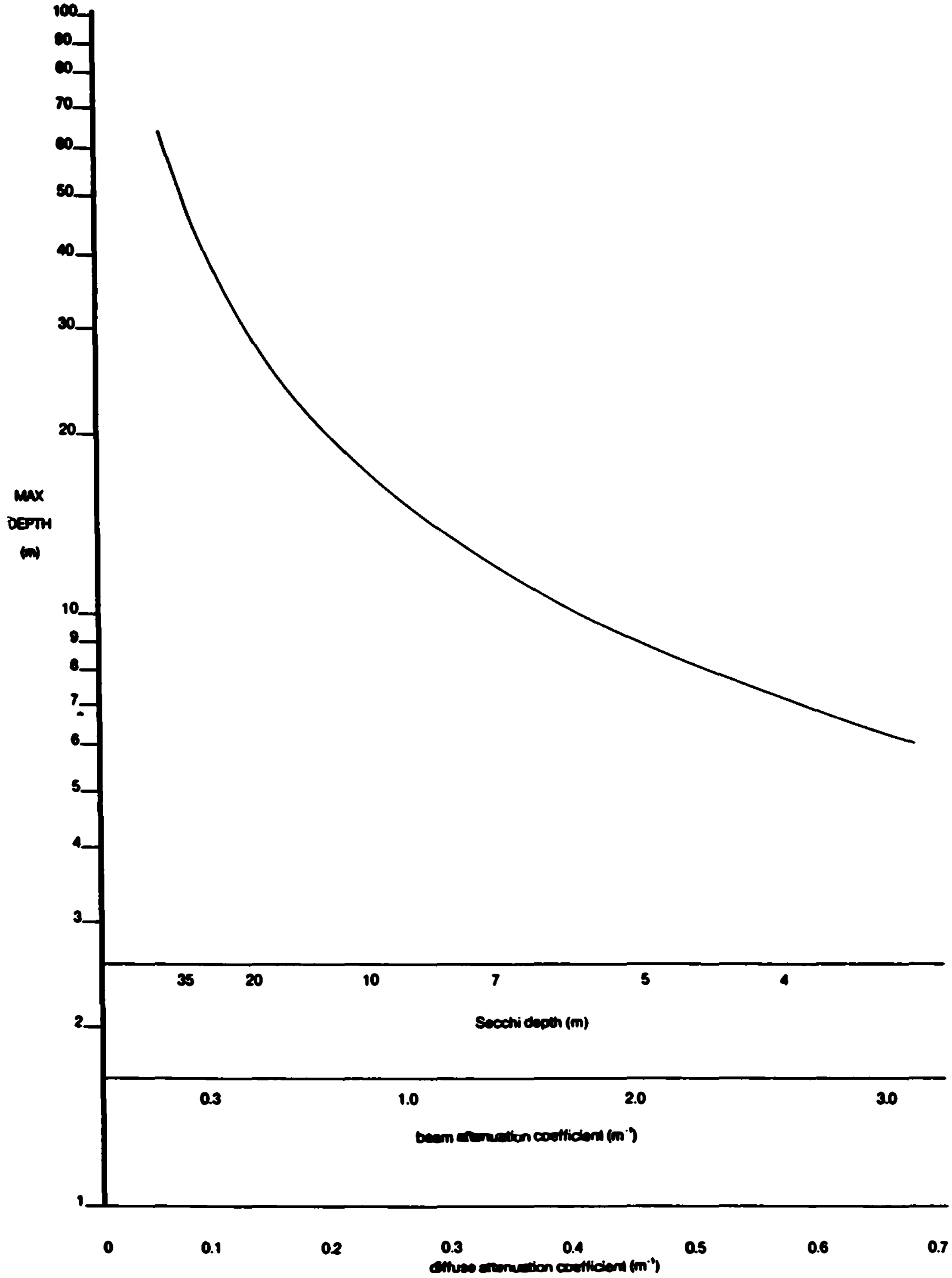


Figure 4-3. Depth penetration versus water clarity

4.4.3 S/N Calculations For The APD Channel

The calculations for the green APD channel show that with $k = 0.55$ m^{-1}, and the other parameters as listed in Table 4-8, a depth of 5 m can be achieved for a $S/N = 3$.

In these calculations, the value of 0.015 for the optical efficiency of the receiver includes a factor 0.3 for the polarizer and a factor 0.1 to account for the fact that only 10% of the received energy is diverted to the green APD channel. Putting $d = 0$ and $\rho = 0.2$ gives a maximum APD current of 6.7 mA, which is acceptable.

Table 4-8

S/N Calculations For APD Channel

TRANSMITTER		DETECTOR	
Pulse Energy (mJ):	5	Responsivity (A/W):	0.25
Pulse Duration (ns):	5	Gain:	75
Optical Efficiency:	0.9	Detector Noise (pA/√Hz):	1.1
		Amplifier Noise (pA/√Hz):	50
		Electronic Bandwidth (MHz):	150
RECEIVER		ENVIRONMENTAL	
Diameter (cm):	20	Aircraft Altitude (m):	200
Field-Of-View (mrad):	10	Diff. Atten. Coeff.(m^{-1}):	0.55
Filter. Bandwidth(A):	10	Bottom Reflectivity:	0.1
Optical Efficiency:	0.015	FOV Loss Factor:	1
		Water Depth (m):	5
		Ambient Radiance ($W/m^2/sr/\mu m$):	2
		Beam Entrance Angle (°):	15
		Signal/Noise:	3.2
		Atm. Atten. Coeff.(km^{-1}):	0.3
CALCULATIONS			
Signal Power (W):	1.4×10^{-7}		
Signal Current(A):	2.6×10^{-6}		
Background Current (A):	1.4×10^{-9}		

4.5 Wave Height Corrections

The wave height will be determined from the variations in the slant range to the surface obtained from the reflected infrared radiation. Swells will be detected using the aircraft vertical accelerometer data to isolate aircraft vertical motion from that of the underlying water surface.

Figure 4-4 illustrates the system geometry. The measured range depends on the altitude difference of the illuminated surface and the aircraft platform, and also on the nadir angle of the beam.

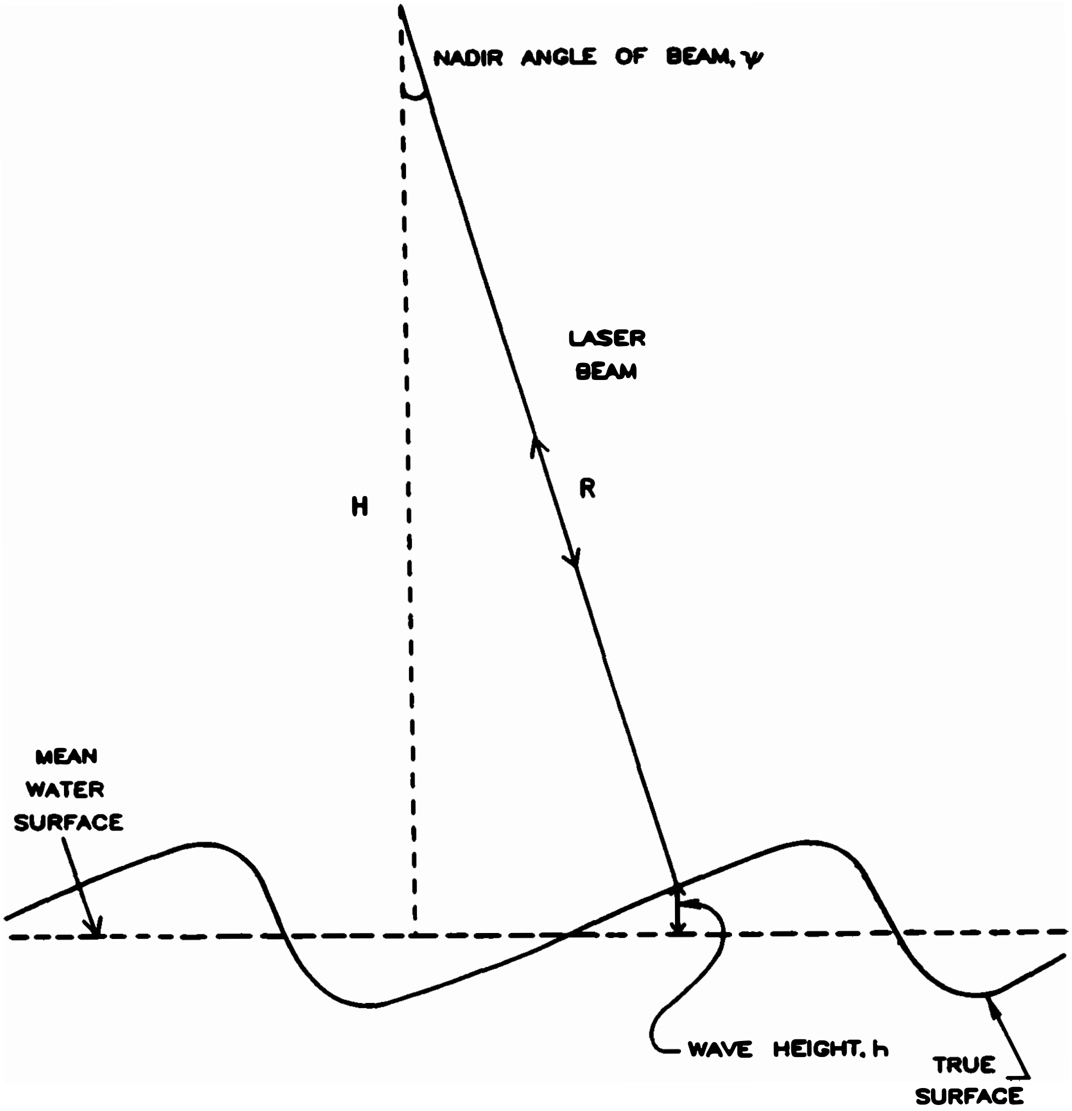


Figure 4-4. Wave correction geometry

Since the objective is to relate the local water surface height to the mean water level, an average level must be determined over a period of time to establish the plane from which the wave height will be estimated.

4.5.1 The Observation Equations

Based on the geometry of Figure 4-4, the following equation can be written:

$$R = (H - h)\sec\psi + \varepsilon, \qquad \text{Equation 4-9}$$

where R is the measured range to the surface,
H is the altitude of the scanning vertex at the aircraft,
ψ is the nadir angle of the beam, represented by θ in Section 3.2
ε represents the error in range, R, and
h is the wave height

Equation 4-9 is sufficient to allow an analysis of the wave height when the scan dimensions on the surface significantly exceed the longest surface wavelength of interest and the aircraft altitude remains essentially constant. In this case, the altitude, H, can be derived for each complete scan as the average value of $R\cos\psi$ and the wave height, h, can be estimated from the individual ranges.

For the expected operating conditions, neither the constancy of the altitude nor the water surface wavelength conditions are likely to be met, and the vertical accelerometer data will be used. The observation equation for this measurement can be written as

$$H = H(t_o) + (t - t_o)\dot{H}(t_o) + \iint a_v \, du dv + \Delta \qquad \text{Equation 4-10}$$

where t is some time following time, t_o
a_v is the vertical acceleration,
Δ is the double integral of the acceleration error.

The dot implies rate of change with time, and u and v are dummy time variables of the double integral from t_o to t.

Note that there are two unknown constants of integration, $H(t_o)$ and $\dot{H}(t_o)$ in Equation 4-10 to account for the double integration. Combining Equation 4-9 and Equation 4-10 we obtain:

$$\begin{aligned} R\cos\psi - \iint a_v \, du dv &= H(t_o) + (t - t_o)\dot{H}(t_o) \\ &\quad + \varepsilon\cos\psi + \Delta - h \qquad \text{Equation 4-11} \\ &= Y_m \end{aligned}$$

This is the combined observation equation which will be used to assess wave height. Initially, we assume that the beam nadir angle ψ is known, in which case the left-hand side of Equation 4-11 is "measured" in the sense that its value can be calculated directly from measurements. Equation 4-11 shows that if we plot this quantity as a function of time the result is a straight line with the addition of the term

$$\varepsilon \cos\psi + \Delta - h.$$

Thus, a linear plot of Y_m against t will provide an estimate of h with the error, $\varepsilon\cos\psi + \Delta$. Figure 4-5 indicates the expected behavior of this graph. The dashed line represents the least-squares straight-line fit to the "measured' Y_m values which are represented by the pluses. A possible set of true values (with the measurement errors eliminated) is indicated by the solid line. A wave crest (or positive h) is indicated where the curve falls below the fitted line while a trough (or negative h) occurs where the curve rises above the fitted line.

It is clear that the fit of Y_m against time must be carried out over a sufficiently long period to cover the longest water surface wavelengths of interest. For example, if we wished to detect wavelength up to 400 m, the aircraft should travel at least twice this distance, or 800 m, during the analysis interval. The actual duration to be employed will be assessed from the aircraft operation and local wave profile conditions.

The fitted value for a straight line fit has its smallest error at the mean value of the abscissa. It follows that the wave height estimate is best evaluated at this point with the fitted value of Y_m being simply the mean value of Y_m in the fitting interval. Thus a computationally efficient procedure would be to maintain a cyclic buffer of Y_m values and estimate the wave heights with a delay (typically 30 or 40 seconds) from the most recent data being analyzed.

4.5.2 Error Reduction

By definition, there will be no bias in the wave height, h, since we require its mean value to be zero. High frequency errors in the range measurement and the accelerometer integral will appear as wave height errors, but it is possible that they may be reduced by a local fitting procedure. A bias in the range or acceleration double integral will be of no consequence to the wave height estimation since the average value of Y_m is removed.

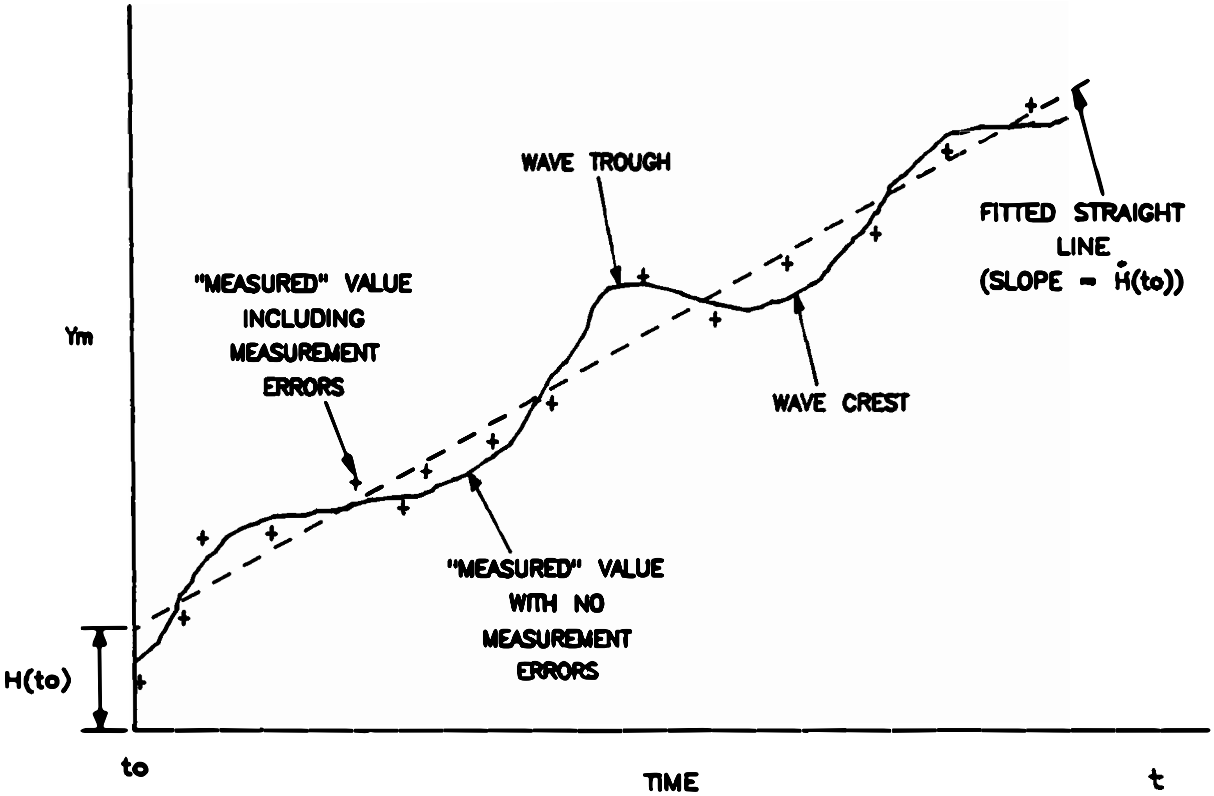


Figure 4-5. A plot of Y_m versus time

It is very important that there be no bias in the vertical acceleration since this would result in a quadratic form of the double integral and a resulting bias in h. This can be tested for and removed, however, by checking the mean value of h over a sufficiently long period and subtracting the mean where necessary.

The greatest potential source for wave height error arises from uncertainties in ψ, the off-nadir angle of the beam. The error in h arising from an error, $\Delta\psi$, in ψ is $R\sin\psi\,\Delta\psi$. If ψ is approximately 15 degrees, then $\sin\psi$ is about 0.25 and in order to reduce the error to around 0.05 m, we would require a determination of ψ with an accuracy of $0.05/(0.25R) = 1/5R$ radians. Therefore, at an altitude of 200 m, the off-nadir angle would have to be determined to an accuracy of 1 milliradian, approximately the same as the roll and pitch measurement error.

4.5.3 Error Budget

The limiting factor affecting wave height accuracy is the range measurement, with an estimated error of 5 to 10 cm, depending on the electronic and wave smoothing parameters. The optical alignment angles, roll and pitch could propagate a larger error however, so these parameters must be accurately determined.

4.6 Minimum Depth Measurement Capability

The usefulness of the HLBS will be enhanced if extremely shoal depths - in the range of 1-1.8 meters - can be accurately measured. The difficulty in measuring such shallow depths arises from the fact that, at some minimum depth, the surface and bottom return signals merge into a single pulse. The ability to resolve surface and bottom returns, at a given depth, depends on the duration and shape of the laser pulse, the relative amplitudes of the signals, and the response time of the receiver.

In order to quantify a measure of minimum depth, a decision must be made on what constitutes an acceptable waveform from which a depth can be estimated. For these merged pulses, a leading-edge bottom detection algorithm would not provide optimal results due to the distortion of the leading edge of the bottom return and the limited number of digitizer amplitude levels above the tail of the surface return. For this purpose peak detection is dictated, even though it is recognized that for separated pulses it is inferior to a leading-edge detector. The minimum measurable depth will thus be the depth at which a clearly-defined dip of several digitizer amplitude units can be discerned between the surface and bottom returns.

The following results are obtained for the various cases of typical values of the laser pulse width, relative amplitudes, and receiver response time.

Case I:

Laser pulse risetime	5.5 ns
PMT risetime	5 ns
Logarithmic amplifier risetime	3 ns
Digitizer risetime	4 ns

The convolution of these four response times gives an RMS value of 9 ns for each of the digitized surface and bottom return signals.

a) For a 1:1 ratio of bottom/surface signal amplitudes, the minimum detectable depth is 1.1 meters.

b) For a 10:1 amplitude ratio, the minimum detectable depth is 1.4 meters.

Given that the 10:1 ratio is much more realistic than the 1:1 case, one would surmise that the minimum resolvable depth for the above set of parameters is 1.4 m, given no significant volume backscatter or surface wave-height variations in the surface spot. The latter effects would somewhat increase this depth.

Case II:

Laser pulse risetime	10 ns
PMT risetime	5 ns
Logarithmic amplifier risetime	3 ns
Digitizer risetime	4 ns

(overall rise time is 12 ns)

a) 1:1 amplitude ratio

Minimum detectable depth = 1.4 m

b) 10:1 amplitude ratio

Minimum detectable depth = 1.9 m

Case III:

Laser pulse risetime	6 ns
PMT risetime	2 ns
Logarithmic amplifier risetime	3 ns
Digitizer risetime	1 ns

(overall risetime = 7 ns)

a) 1:1 amplitude ratio

Minimum detectable depth is less than 1 meter

b) 10:1 amplitude ratio

Minimum detectable depth is 1 meter

The theoretically achievable minimum depth, as a function of the amplitude ratio of the bottom and surface return pulses, is shown in Figure 4-6 and Figure 4-7 for the two cases of 7.1 and 10.7 ns combined response time. This analysis was done by combining two pulses of the same risetime and determining the minimum separation at which the pulses could be resolved. The resolution criterion is that the derivative changes sign three times. In practice, the minimum achievable depth is somewhat larger than these plots show.

In conclusion, the minimum depth measurement capability of the system will be in the range of 1-1.5 m, depending on the exact risetimes achievable for the laser pulse and detector.

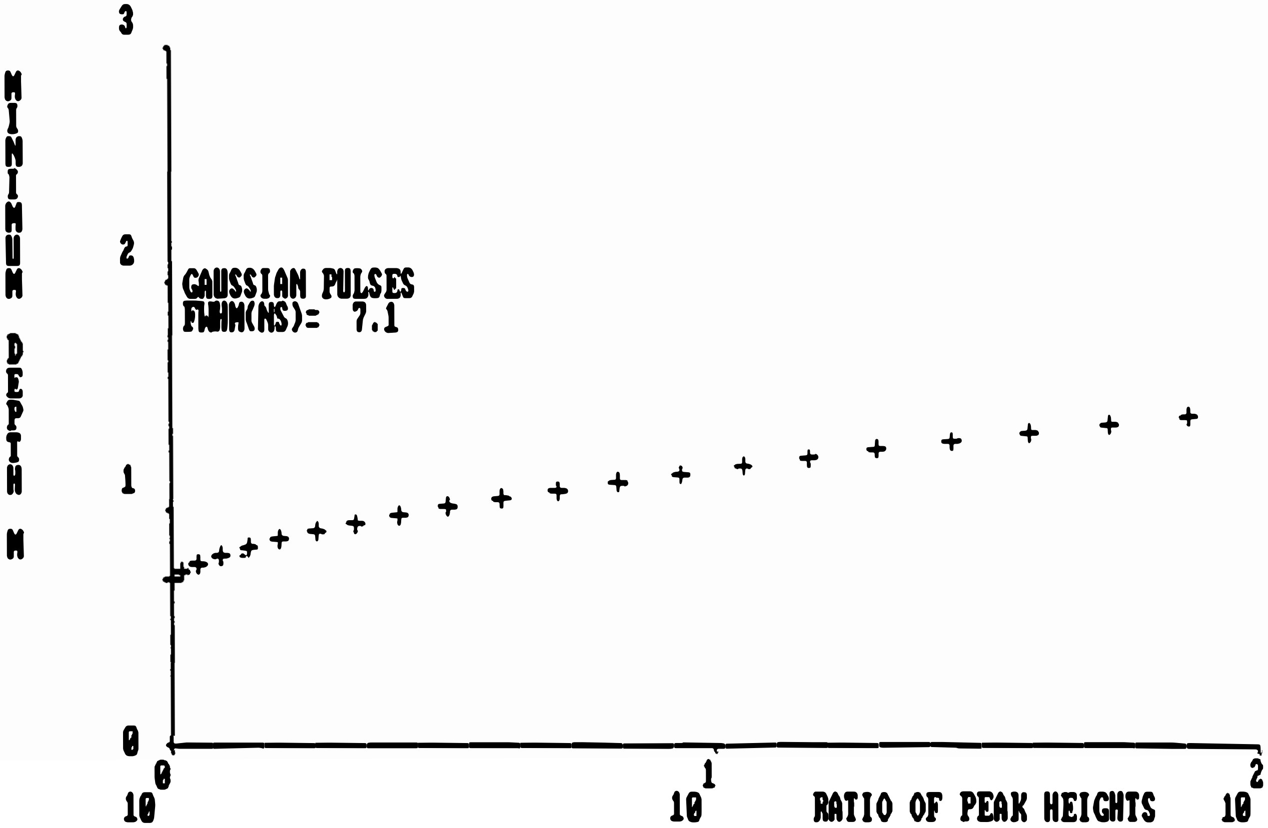


Figure 4-6. Minimum depth versus amplitude ratio for 7.1 ns pulses

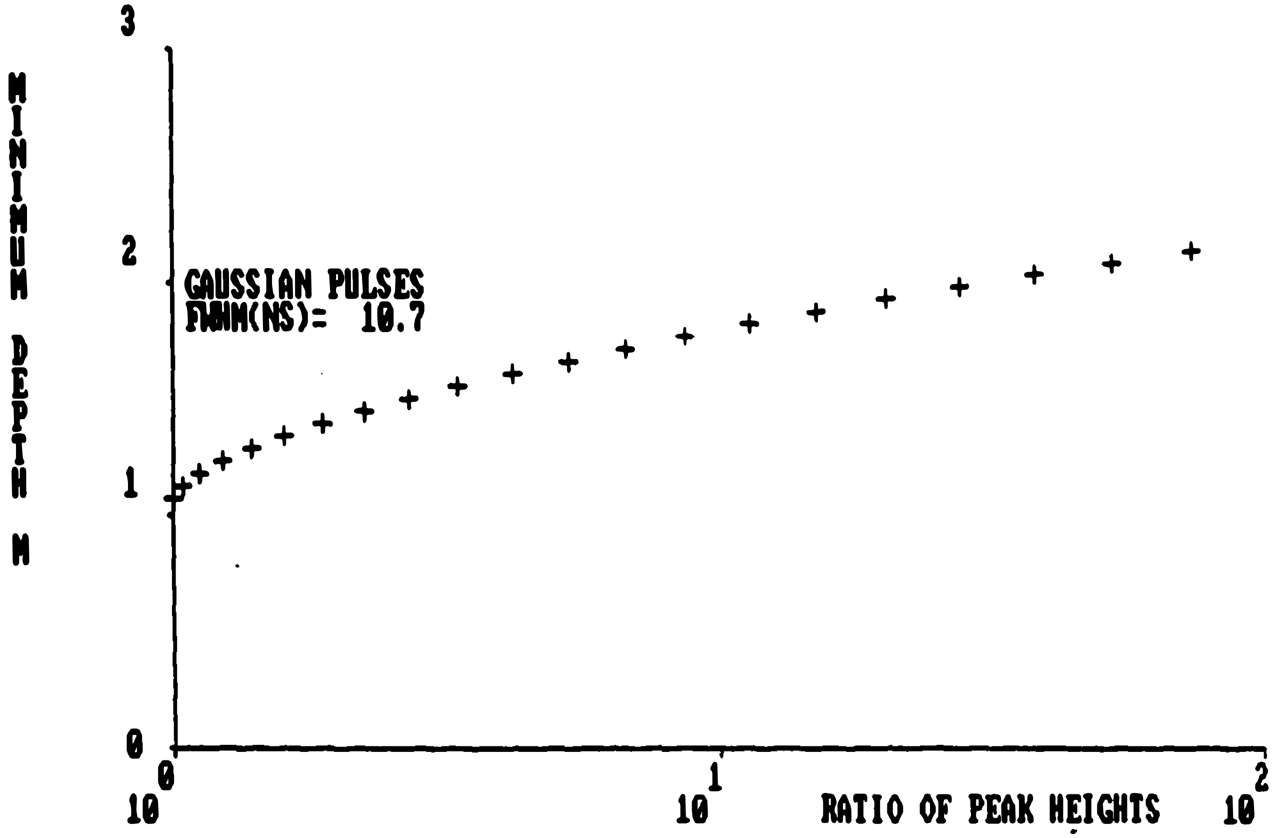


Figure 4-7. Minimum depth versus amplitude ratio for 10.7 ns pulses

4.7 Eye Safety Considerations

According to United States Food and Drug Administration (FDA) the HLBS system will be categorized as a Class IV laser product. As such, all the safety features required by the FDA in Titles 21CFR1040.10 and 1040.11 will be incorporated. They are listed in Table 4-9.

Table 4-9
HLBS Protective Safety Features

1. Protective housing to block the laser beam when it is not being used in its intended application
2. Safety interlocks on all removable panels that would result in exposure to the laser beam
3. A key-lock switch to operate the laser. The key will only be removable in the OFF position
4. Remote interlock capabilities
5. Laser emission indicator lamp
6. Shutter system to block the beam with a manual reset required to open the shutter
7. Warning labels appropriately placed

Because of the low normal operational altitude of the proposed HLBS and the high energy of the laser beam, care must be taken to ensure that the system remains eyesafe to observers on the ground. This is an important concern considering the locales in which the system will typically be employed. To ensure that the system will be eye-safe at ground level, the laser divergence will be automatically adjusted according to the altitude at which the system operates so as to achieve eye-safe levels. Safety calculations have been performed in accordance with ANSI Z136.1-1986 guidelines. They have been based on the performance specifications of the laser, which are presented in Table 4-10.

Table 4-10
Laser MPE Calculation Factors

Pulse Width:	5 nsec
Energy:	5 mJ at 532 nm 15 mJ at 1064 nm
Laser Repetition Rate:	200 Hz
Initial Beam Diameter:	a = 1 cm
Divergence:	ϕ mrad
Altitude:	r meters

The first parameter that must be taken into account is the Maximum Permissible Exposure (MPE) for the wavelengths of radiation of concern. For single pulses of 5 ns duration, the MPE values for the 532-nm and 1064-nm wavelengths are 5×10^{-7} J/cm^2 and 5×10^{-6} J/cm^2, respectively. For a repetitively-pulsed laser these values must be decreased by the factor $n^{-1/4}$, where n is the number of pulses during the exposure duration, t. At a wavelength of 532 nm the aversion response time of 0.25 seconds defines t whereas for 1064 nm an exposure duration of 10 seconds must be used.

Thus for a 200 Hz laser pulse repetition rate and a wavelength of 532 nm, the MPE value is given by:

$$\begin{aligned} \text{MPE} &= [(200)(0.25)]^{-1/4} \times (5 \times 10^{-7}) \text{ J/cm}^2 \\ &= 1.88 \times 10^{-7} \text{ J/cm}^2 \end{aligned}$$

Equation 4-12

The MPE values for 5- and 200-Hz operation at 532 and 1064 nm are shown in Table 4-11.

Table 4-11
MPE Values for 5-Hz and 200-Hz Laser Operation

Wavelength	5 Hz	200 Hz
532 nm	4.73×10^{-7} J/cm^2	1.88×10^{-7} J/cm^2
1064 nm	1.88×10^{-6} J/cm^2	7.48×10^{-7} J/cm^2

The range-divergence equation to be satisfied is given in the ANSI guide as:

$$r\phi = \left[\frac{4\,E}{\pi(\text{MPE})}\right]^{1/2} - a$$

Equation 4-13

Thus for a given energy, MPE and initial beam diameter, the rϕ product is constant. For example, for a wavelength of 532 nm and a repetition rate of 200 Hz, the parameters above predict a rϕ product of:

$$\left[\frac{[4\ (5 \times 10^{-3}\ J)]}{\pi(1.88 \times 10^{-7})\ J\ cm^{-2}}\right]^{1/2} - 1\ cm = 183\ cm.rad$$

Equation 4-14

This value can be expressed more meaningfully as 1830 m-mrad. This means that a laser beam divergence of 10 mrad will require an altitude of greater than 183 meters to be eyesafe. The other three values of interest are calculated and presented in Table 4-12.

Table 4-12
Altitude-Beam-Divergence Products

Wavelength	5 Hz	200 Hz
532 nm	1150 m-mrad	1830 m-mrad
1064 nm	998 m-mrad	1590 m-mrad

The 200-Hz values will apply if the helicopter is hovering and the laser is not scanning. When the laser is scanning, the 5-Hz values can be used. If the divergence were 10 mrad, a scanning system would be eyesafe at 115 meters, but a non-scanning system would have to increase altitude to 183 meters.

It can be seen from Table 4-11 and Table 4-12 that the visible radiation is the most dangerous to the human eye. However, if the energy in the infrared were more than four times the energy in the visible, the invisible radiation would have the higher eye-safe altitude.

For the sake of completeness, the altitude divergence product can also be calculated based on single pulses. This can happen in test situations or if the helicopter moves fast enough so that it is impossible for anyone on the surface to see more than one laser pulse. Using the single-pulse MPE values and the parameters provided, a value of 1120 m-mrad for 532 nm and 610 m-mrad for 1064 nm is calculated. The single pulse eye-safe altitude at the visible green wavelength does not decrease significantly compared to the 5 Hz value at 532 nm.

SECTION 5.0

PRELIMINARY DESIGN

The Helicopter Lidar Bathymeter System (HLBS) is composed of the following subsystems:

1. Transceiver subsystem (TRS), consisting of transmitter, scanner, receiver optics, receiver electronics and video camera

   Receiver electronics include real-time signal processing (RTSP), consisting of log amp and time interval counter to measure the time of flight of the laser pulse, and hence the slant range to the water surface.

2. Acquisition, control and display subsystem, including the airborne computer system which controls the HLBS, provides an operator interface and is responsible for the acquisition and recording of survey data; also includes the digitizer, which samples and digitizes the reflected optical return signals

3. Positioning system to determine the aircraft's co-ordinates, and inertial reference system to determine aircraft attitude and vertical acceleration

4. Ground-based data processing system (DPS) to process and display the acquired data, and produce final lidar data in a digital XYZ database

A block schematic of the airborne portion of HLBS is presented in Figure 5-1.

5.1 Transceiver Subsystem

The transceiver consists of the transmitter, scanner, receiver optics and electronics, and the video camera. It will be mounted in a light-weight rigid frame, to permit quick and easy installation in, and removal from, the helicopter. It will be designed for installation on isolation mounts to minimize the effects of vibration. Re-alignment of the optical elements after installation will not be necessary.

5.1.1 Transmitter

The transmitter consists of the laser, beam divergence controller and beam steering optics.

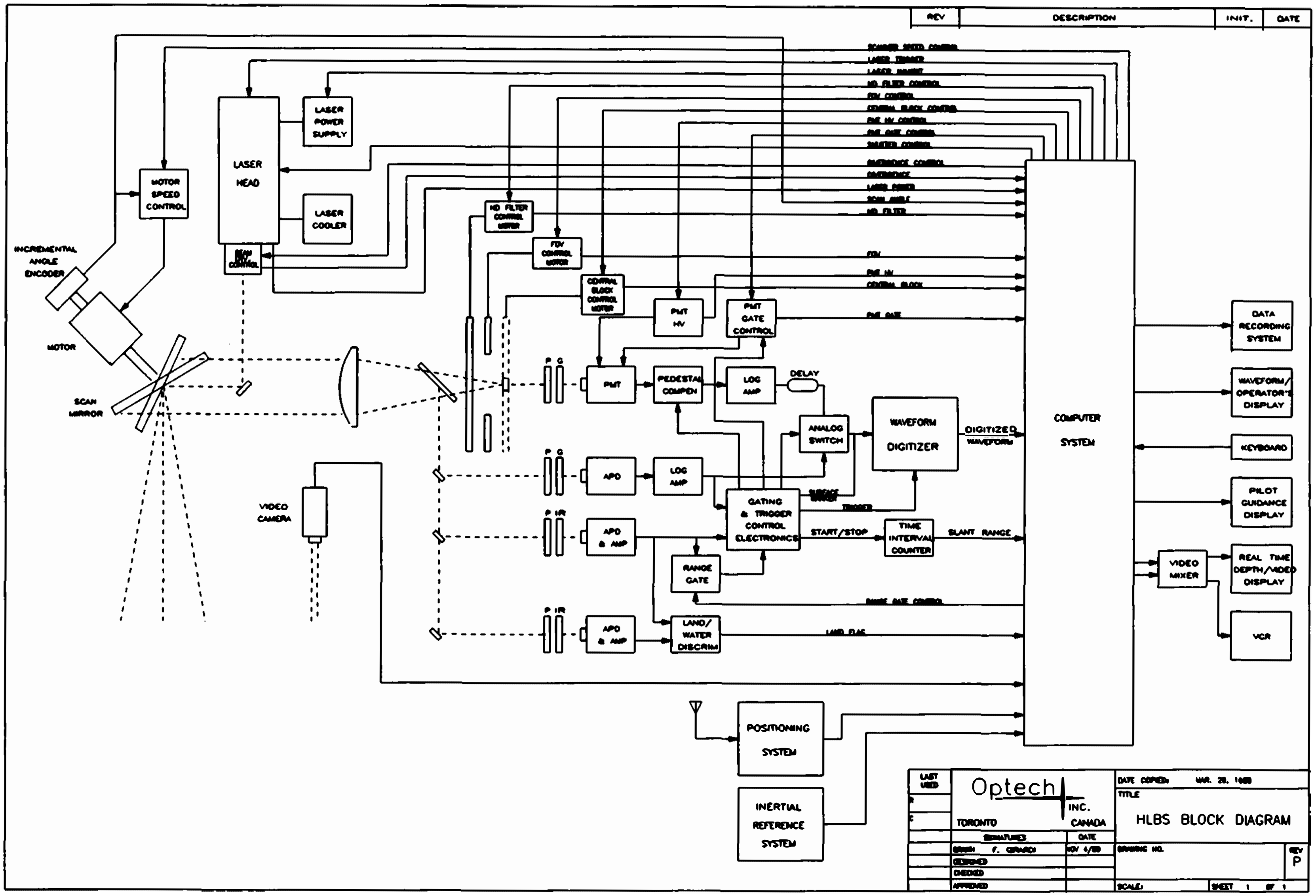


Figure 5-1. Airborne Lidar Bathymeter System

5.1.1.1 Laser

The HLBS will use a frequency-doubled Nd:YAG laser which produces a fundamental output at 1064 nm (near IR) and a doubled (green) output at 532 nm. The outputs at the two wavelengths are collinear. The laser will have a maximum repetition rate of 200 Hz and will be externally triggered by the computer system.

The wavelength of the green output, which very nearly coincides with the optimum wavelength for maximum depth penetration in seawater, will be used to obtain the bottom return. The IR output, reflected from the water surface, will be used for timing purposes, as explained later.

The laser will be Q-switched in order to produce the high peak power and narrow pulse required for the HLBS. High peak power is necessary to maximize the depth penetration. The narrow pulse width is required to enable the measurement of shallow depths.

The system will use a custom version of the state-of-the-art flashlamp-pumped Q-switched Nd:YAG laser. The laser will require a closed-loop liquid cooling system. A laser shot counter will indicate when the flashlamp must be replaced, after approximately 10 million shots. Optech is closely monitoring advances made in the development of diode-pumped lasers, but no suitable versions have yet been commercially manufactured.

The specifications to which the laser will be built are summarized in Table 5-1.

Table 5-1
Laser Specifications

Energy Per Pulse:	Green wavelength	5 mJ, nominal
	IR wavelength	15 mJ
Pulse Width (FWHM):	5 ns, nominal	
Laser Repetition Rate:	200 Hz, nominal	
Maximum Input Power:	2.5 kW	
Pump Lifetime:	At least 10^7 pulses before pulse energy drops to 50% of peak value	
Pulse Tail Amplitude:	< 1% at 20 ns after peak < 0.1% at 50 ns after peak	
Pulse Amplitude Jitter:	< 5% RMS	

5.1.1.2 Beam Divergence Controller

The divergence of the laser beam will be continuously variable over the range of two to ten milliradians. Alignment of the divergence control module with the beam will be such that less than one milliradian of beam wander will be incurred over the full range of the divergence adjustment. The divergence controller will be controlled by the computer and will provide it with the divergence value. The divergence value at the two wavelengths will be the same to within 30%.

The controller, a collimating telescope mounted on the output of the laser, will consist of a short focal length concave lens assembly and a longer focal length convex lens assembly.

5.1.1.3 Beam Steering Optics

The output beam from the laser will be directed through the beam divergence controller onto the beam steering optics consisting of an adjustable mirror, M1, one or more fixed mirrors, M2, and the scanner mirror. A schematic diagram of the beam steering optics is presented in Figure 5-2.

5.1.2 Scanner

The scanner consists of a mirror, motor, motor speed controller and angle encoder, all integrated by a mechanical assembly.

The rotating inclined mirror will project a scan pattern on the water (or land) surface. Figure 5-3 shows the mechanical arrangement of the scanner. The rotation axis is inclined at an angle, β, to the horizontal, and the mirror normal is inclined at an angle, α, to the rotation axis. The laser beam is incident from the right. The angles α and β are chosen to produce an off-nadir angle in the range of 15-25 degrees, in order to minimize propagation-induced depth bias errors and maximize sounding density.

The scanner mirror reflects the two collinear outputs of the laser (532 and 1064 nm) onto the target surface and also reflects the energy returned from the target, which arrives at the mirror a few microseconds later, into the receiver telescope.

The forward motion of the aircraft, together with the nutating motion of the scanner, gives complete coverage in both the X and Y directions. The rotation rate of the mirror, 1-5 Hz, and the laser firing sequence, at pre-determined angular positions of the mirror, will be computer controlled and chosen as a function of aircraft altitude and speed to provide a quasi-uniform spacing on the water surface.

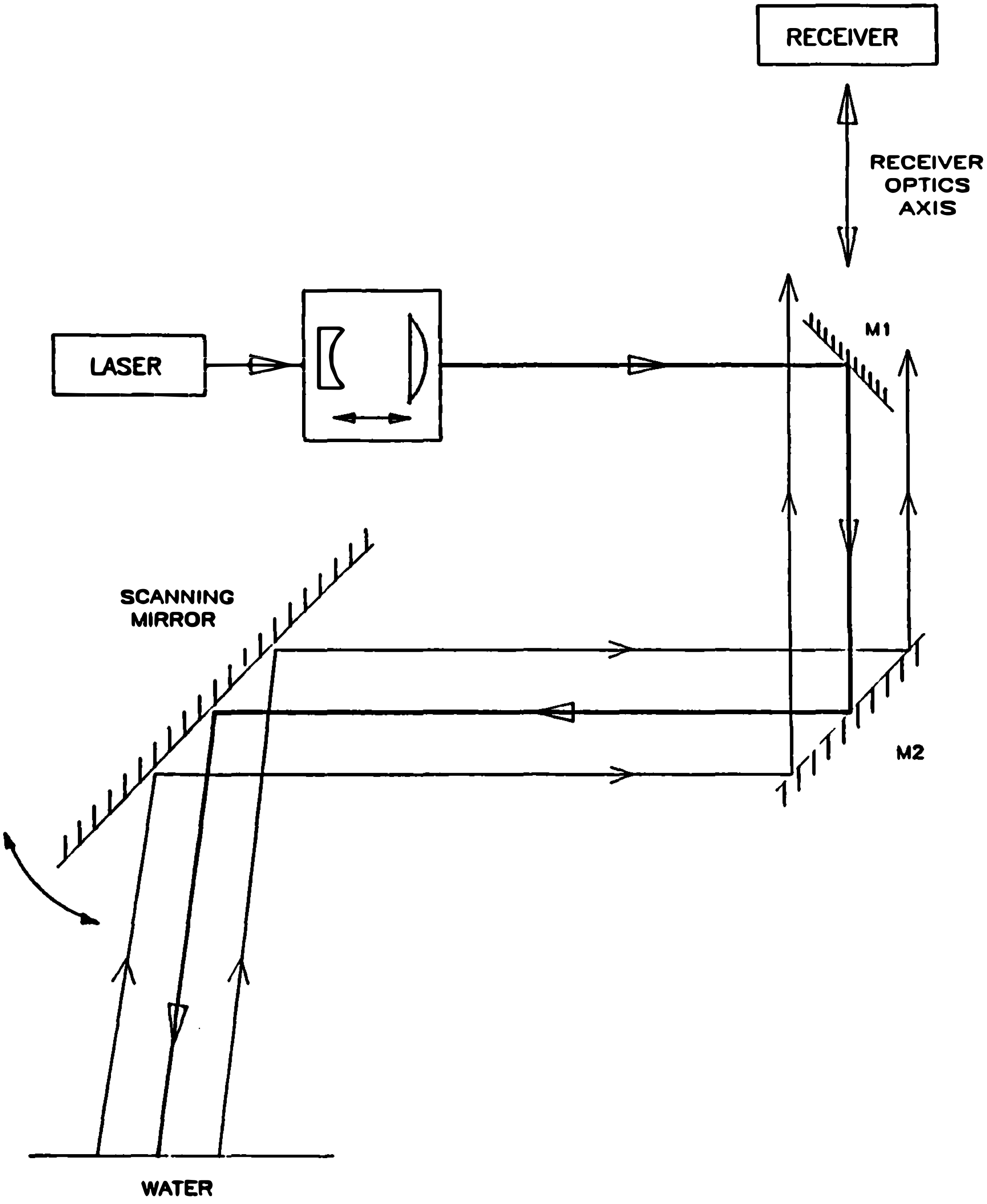


Figure 5-2. Beam steering optics

The scanner will operate in two modes, selectable at the main computer terminal. The scanning mode will allow for fast coverage of large areas. The non-scanning, or profiling, mode will allow for dense coverage of specific areas with a corresponding increase in detail along the line of flight.

The scanner will consist of a belt-driven rotating mirror assembly and a +28 VDC motor with electronic speed control. The motor controller will use feedback from a 14-bit incremental angle encoder, attached to the mirror shaft, to keep the motor speed constant. An angle encoder interface circuit will produce a zero reference pulse once per revolution, together with incremental angle pulses. These will be used by the computer system to generate laser trigger pulses at specific scan angles and to determine the scanner rotation rate. The revolution and angular shot number are recorded by the computer.

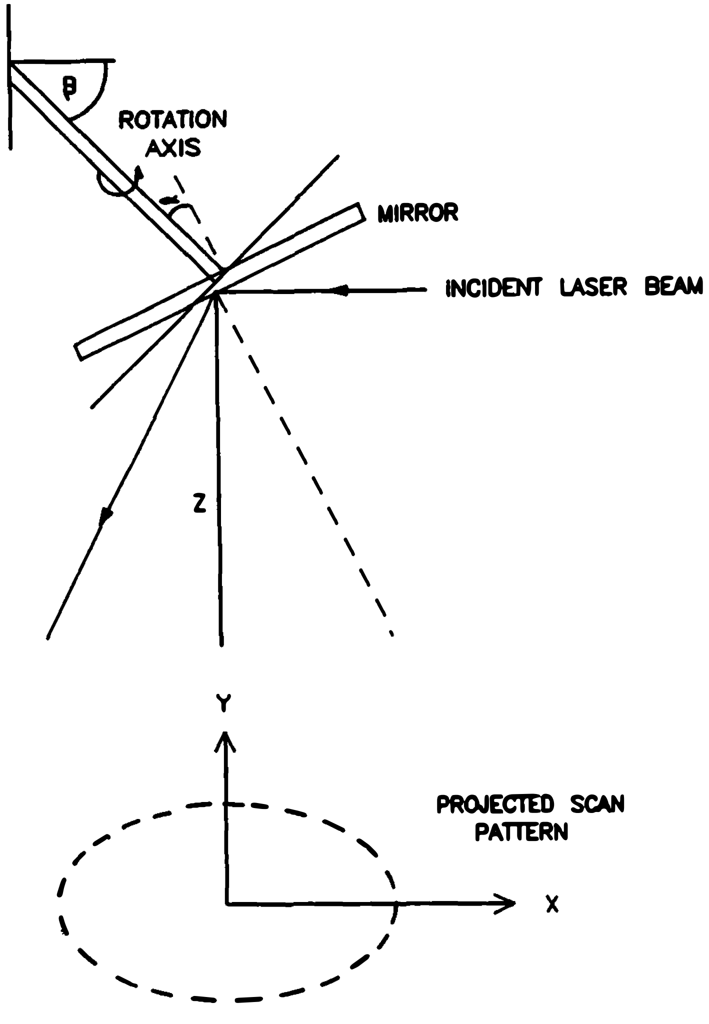
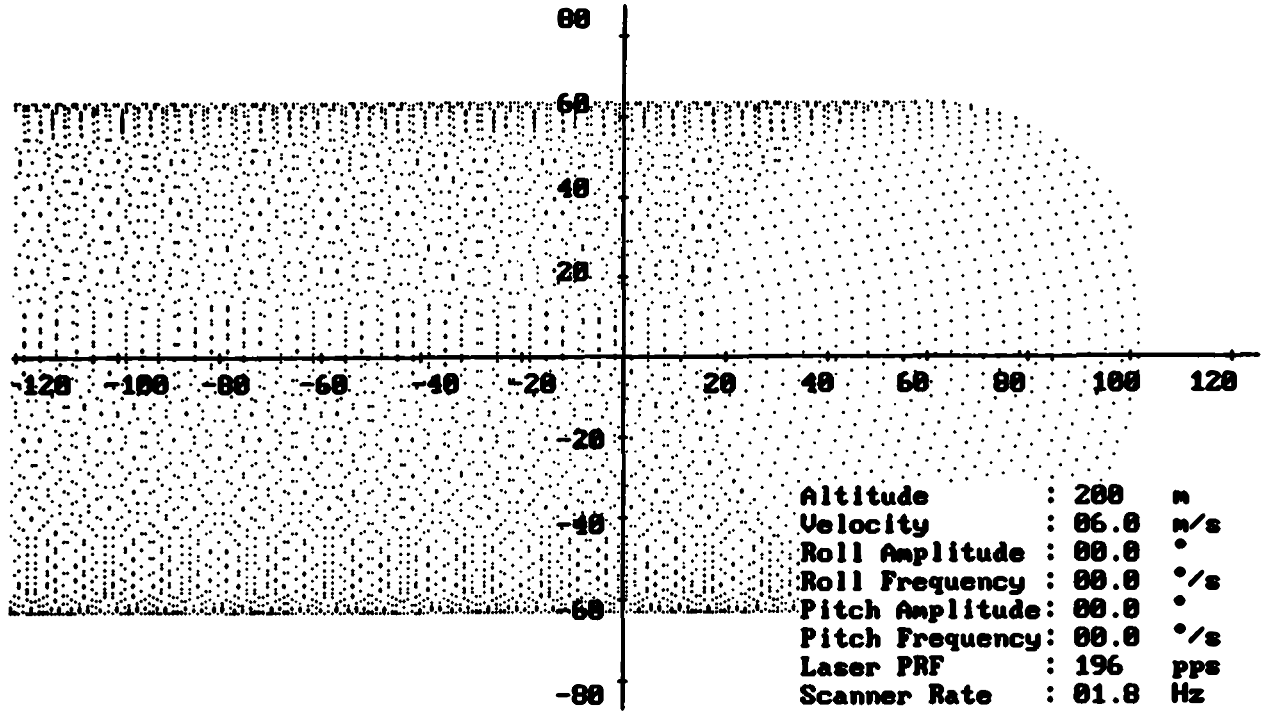


Figure 5-3. Scanner configuration

The laser will be triggered by the computer at predetermined angular positions of the scan mirror, as measured by the angle encoder. After the operating altitude and the aircraft speed have been entered, default values will be assigned to the laser repetition rate and firing pattern. The operator will be able to view the resulting scan pattern on the display console and adjust the laser repetition rate and firing pattern if the scan coverage is inadequate.

Figures 5-4 to 5-7 present computed scan patterns to illustrate the effects of altitude on the swath width, and the effects of aircraft speed and scanner rotation rate on the spot density. Also shown is the effect of aircraft roll and pitch.

Figure 5-4 shows the pattern for an aircraft altitude of 200 meters, a ground speed of 6 m/s (12 knots), a scanning mirror rotation rate of 1.8 revolutions per second, and a resulting laser repetition rate of 196 pulses per second. Note that the scale for both axes is in meters, and the aircraft is moving from left to right. The width of the scan swath in this case is approximately 125 meters. The resulting spot spacing is about three meters in the region of no overlap, and slightly less in the overlapped region.

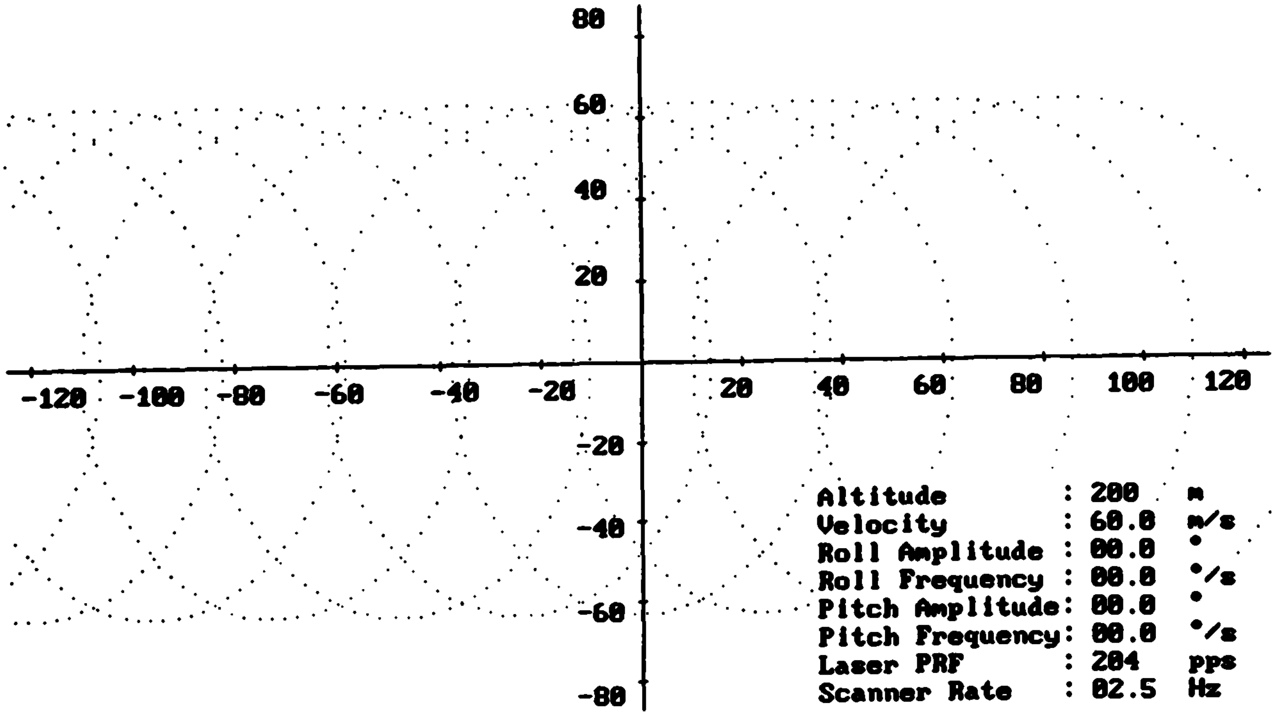


Altitude : 200 m
Velocity : 06.0 m/s
Roll Amplitude : 00.0 °
Roll Frequency : 00.0 °/s
Pitch Amplitude : 00.0 °
Pitch Frequency : 00.0 °/s
Laser PRF : 196 pps
Scanner Rate : 01.8 Hz

Figure 5-4. Scan pattern, altitude = 200 m, velocity = 06.0 m/s

The same density can be achieved using an altitude of 100 meters, an aircraft speed of 10 m/s and a scan rate of 3.5 Hz. The swath width is then half that in the previous case. This gives the system the flexibility of choosing a particular set of parameters that may be easier to achieve, in order to meet the same requirements.

Figure 5-5 shows the pattern generated using an altitude of 200 meters, a velocity of 60 m/s (120 knots), and a scan rate of 2.5 Hz. Such a pattern can be generated if the sounding density across the swath is desired to be significantly higher than along the flightline. This resembles typical requirements for a high-density cross-channel survey (e.g. ten-foot spacing across the channel and 100-foot spacing along the channel).



Altitude : 200 m
Velocity : 60.0 m/s
Roll Amplitude : 00.0 °
Roll Frequency : 00.0 °/s
Pitch Amplitude: 00.0 °
Pitch Frequency: 00.0 °/s
Laser PRF : 204 pps
Scanner Rate : 02.5 Hz

Figure 5-5. Scan pattern, altitude = 200 m, velocity = 60.0 m/s

The scan pattern in Figure 5-6 is for an altitude of 500 meters, a velocity of 70 m/s (140 knots) and a scan rate of 3.5 Hz. This scanning mode is appropriate for surveys requiring lower density with a higher coverage rate. Here, the average spot spacing is roughly 15 meters, and the area covered is a 320-meter wide swath at a rate of 140 nautical miles per hour (80 km²/hr).

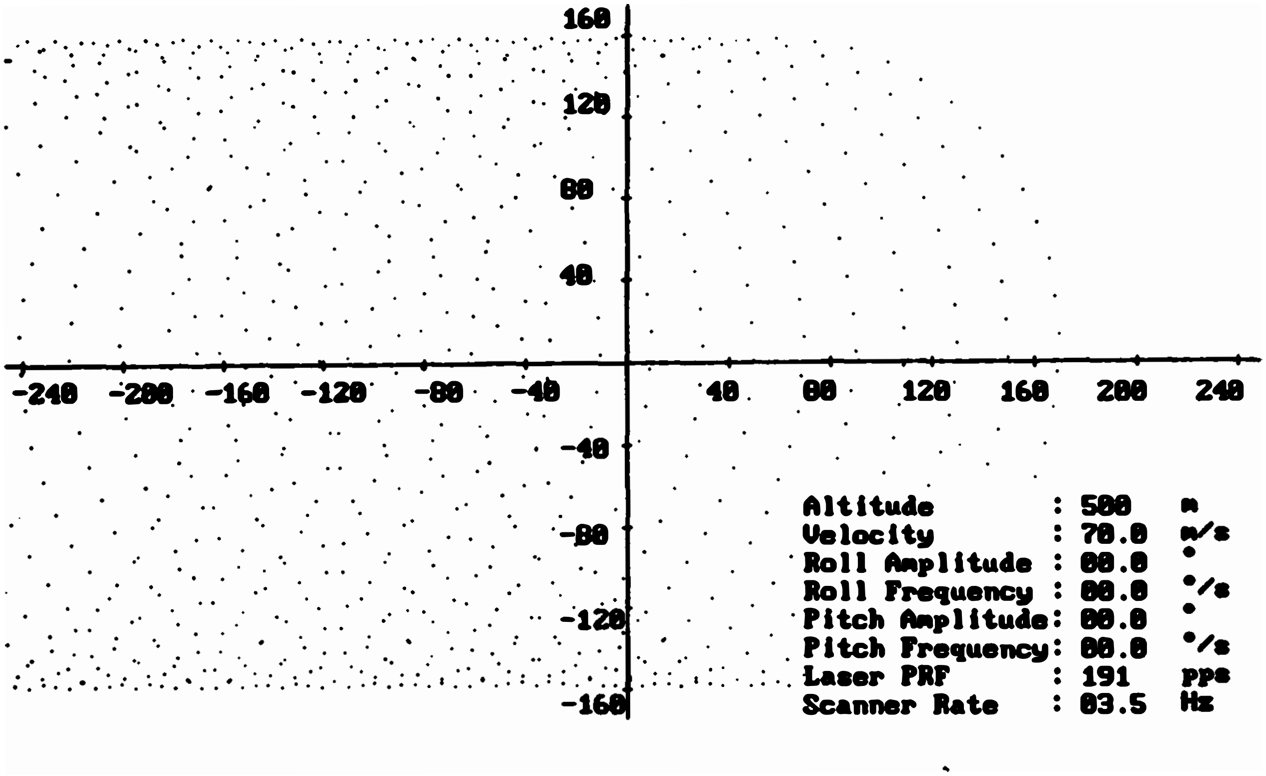


Figure 5-6. Scan pattern, altitude = 500 m, velocity 70.0 m/s

The above scan patterns were generated for no roll and pitch of the aircraft. Figure 5-7 illustrates the effect of roll and pitch on the scan pattern. To simplify the simulation, a sinusoidal roll and pitch variation with time has been chosen.

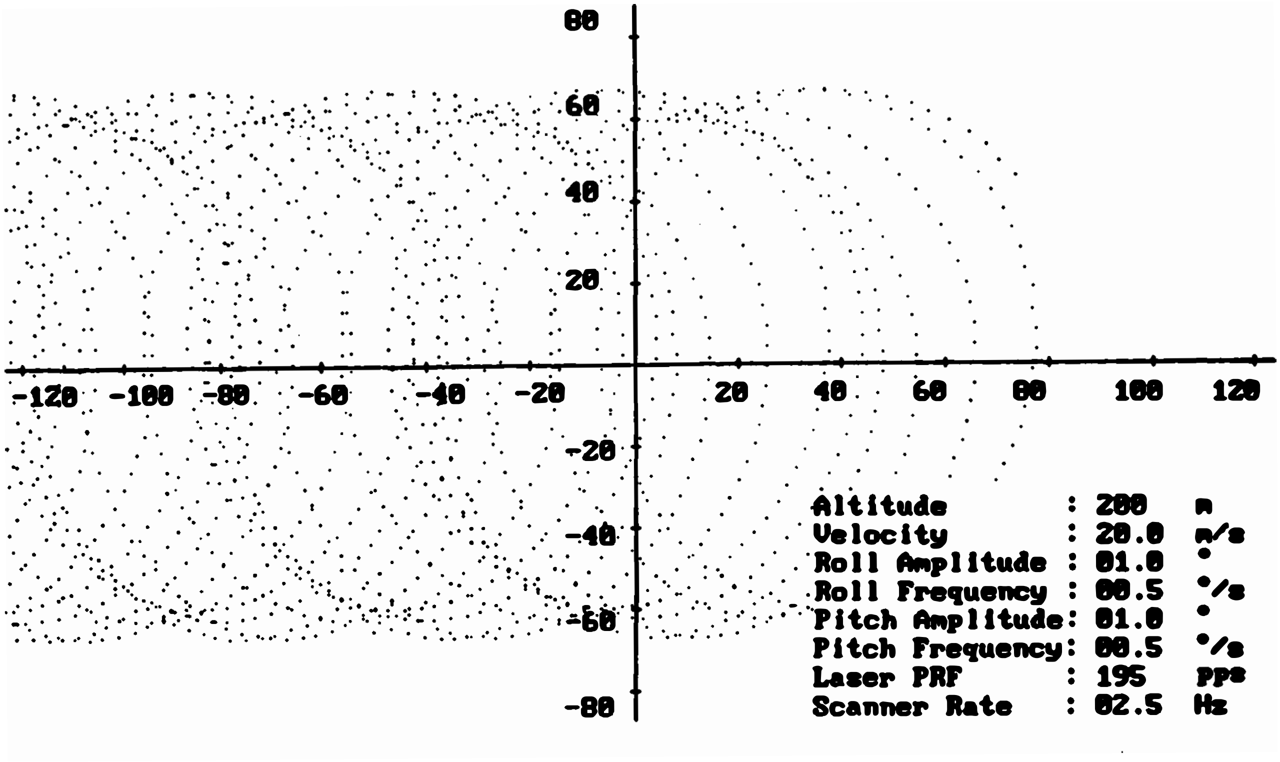


Figure 5-7. Scan pattern, altitude = 200 m, velocity 20.0 m/s

5.1.3 Receiver Optics

The receiver optics will collect, separate, direct and focus the reflected optical signals onto four detectors, and will perform the required spectral and spatial filtering. A detailed diagram of the primary and secondary optical system is presented in Figure 5-8.

The primary optical system, or telescope, will collect the reflected infrared and backscattered green radiation. The telescope will consist of primary and secondary mirrors and a corrector lens.

The secondary optics will separate the reflected beam into its two component wavelengths and direct them to appropriate detectors. The 532 nm backscattered green radiation will be reflected onto a photomultiplier tube (PMT) and onto an optional avalanche photodiode, APD1. The 1064 nm infrared radiation reflected from the water surface will be directed onto two separate infrared APD detectors, APD2 and APD3.

Narrowband interference filters will block solar radiation, ensuring that the maximum signal/noise ratio is obtained.

The PMT's field of view will be adjusted by a variable field stop in the focal plane of the telescope. The field stop will be a motor-driven iris controlled by the computer.

Special optical techniques will reduce the dynamic range of the return signal and prevent saturation of the detectors. A spatial filter (central block) behind the field stop will, to a certain extent, prevent the strong green radiation from the water surface from entering the PMT while allowing subsurface backscattered radiation to pass. This is effective because return energy from surface reflections occurs in a field-of-view approximately equal to the divergence of the laser beam, whereas return energy from bottom reflections occurs in a much larger field-of-view due to the spreading of the beam as it propagates through the water column. Test results have shown that a reduction of surface returns by a factor of up to 30 can be achieved with a spatial block without seriously affecting bottom returns. The computer will automatically match the size of the spatial block to the laser divergence.

The amplitude of the surface return will be further reduced by making use of the differences in polarization between specular reflections and the backscattered bottom returns. Specular reflections from the surface, which are linearly polarized, will be attenuated by a crossed polarizer in the green channel of the receiver. Bottom optical returns, which are unpolarized, will not be strongly attenuated and will pass through to the photomultiplier.

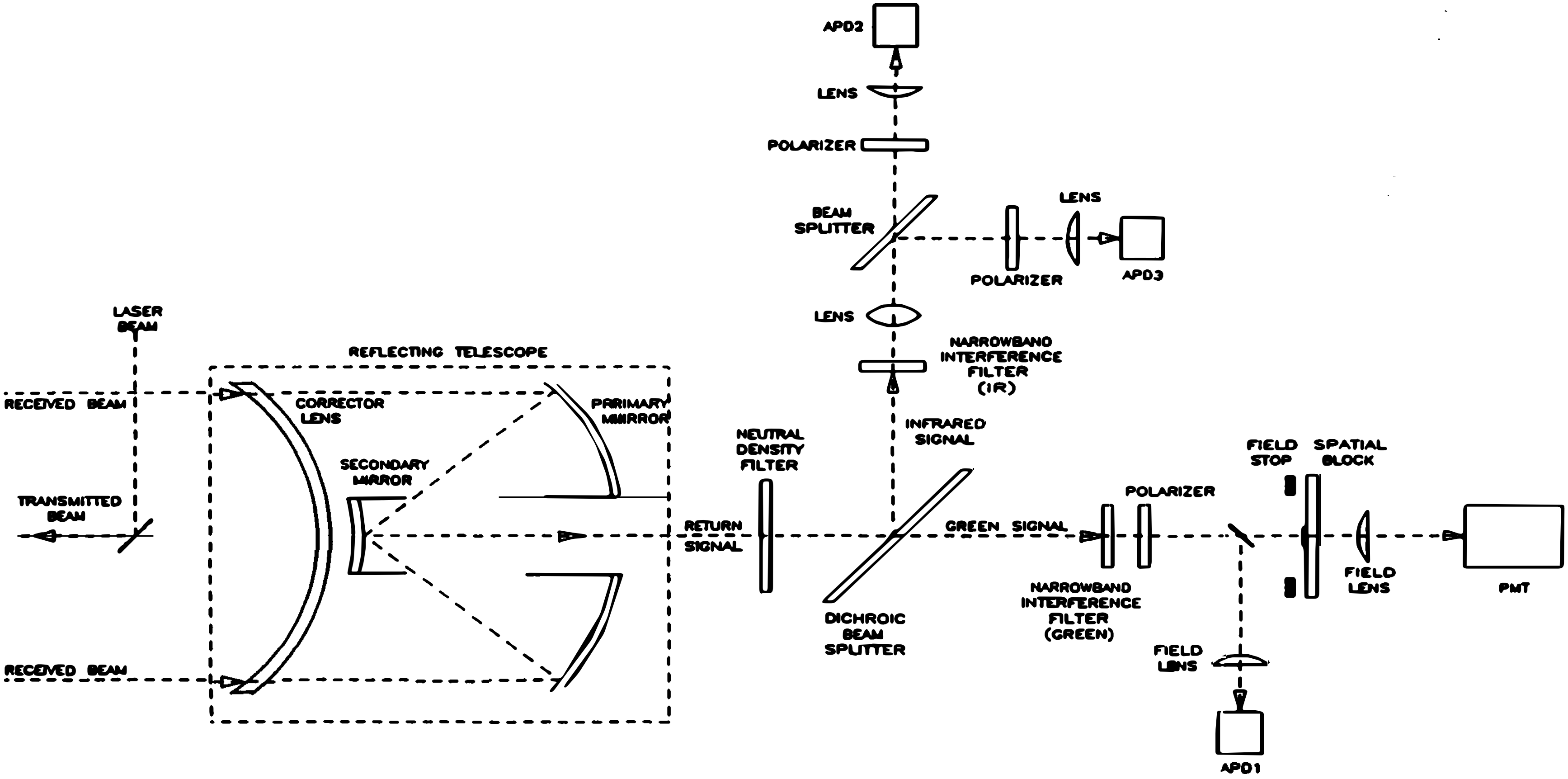


Figure 5-8. Receiver optical system

Since the spatial filters will block most of the return energy from the central part of the field-of-view, the PMT will not receive much backscattered radiation from shallower water depths. In addition, in order to optimize the minimum depth measurement capability of the system, a detector with a fast rise time will be required. Based on past experience, however, we have found the need to reduce the gain,. and hence the high voltage, of the PMT under certain operating conditions. This will lead to an increase in PMT risetime. For these reasons, it is recommended that a second green channel be used for depth soundings in water up to five meters deep. This channel will use an avalanche photodiode, APD1, with an appropriate spectral response, a risetime of less than two nanoseconds and a field-of-view of about ten milliradians. It will be evaluated during field tests and used operationally only if the PMT channel, by itself, cannot meet the desired minimum depth or dynamic range requirements of the system.

5.1.4 Receiver Electronics

The receiver electronics unit will prepare the optical subsurface return signals for digital conversion and further processing by the computer. It will generate triggering and timing signals, as well as data flags for receiver circuit gating and data process control. The combined waveform containing subsurface and surface return signals will be used to extract the water depth.

The optical radiation collected by the telescope will be divided among four detection channels. Two channels will detect and condition the backscattered radiation at the green wavelength; two other channels will detect and process backscattered infrared radiation. The subsurface return waveforms are visible only in channels detecting the green radiation, as the infrared detection channels do not see beyond the surface. The receiver electronics functions are presented in depth in Figure 5-9.

The receiver timing will be referenced to the laser fired pulse and the surface return pulse. All signals detected in the interval between these two pulses will be ignored. A detailed timing diagram is presented in Figure 5-10.

Two types of photodetectors will be employed, depending upon the dynamic range and the field-of-view requirements of the detection channel. A photomultiplier tube (PMT) will be the primary detector for radiation backscattered from the water column and bottom. It will be capable of operating in gated mode to prevent saturation under conditions of high intensity background light. The selection of gating mode will be done by the computer, which will also adjust the PMT high voltage power supply. This power supply controls the PMT gain and hence the propagation delay through the PMT.

In gated mode, a pulse produced by the PMT gate generator will turn the PMT off during the strong surface return signal, and on to receive the backscattered signals from the water bottom. However,

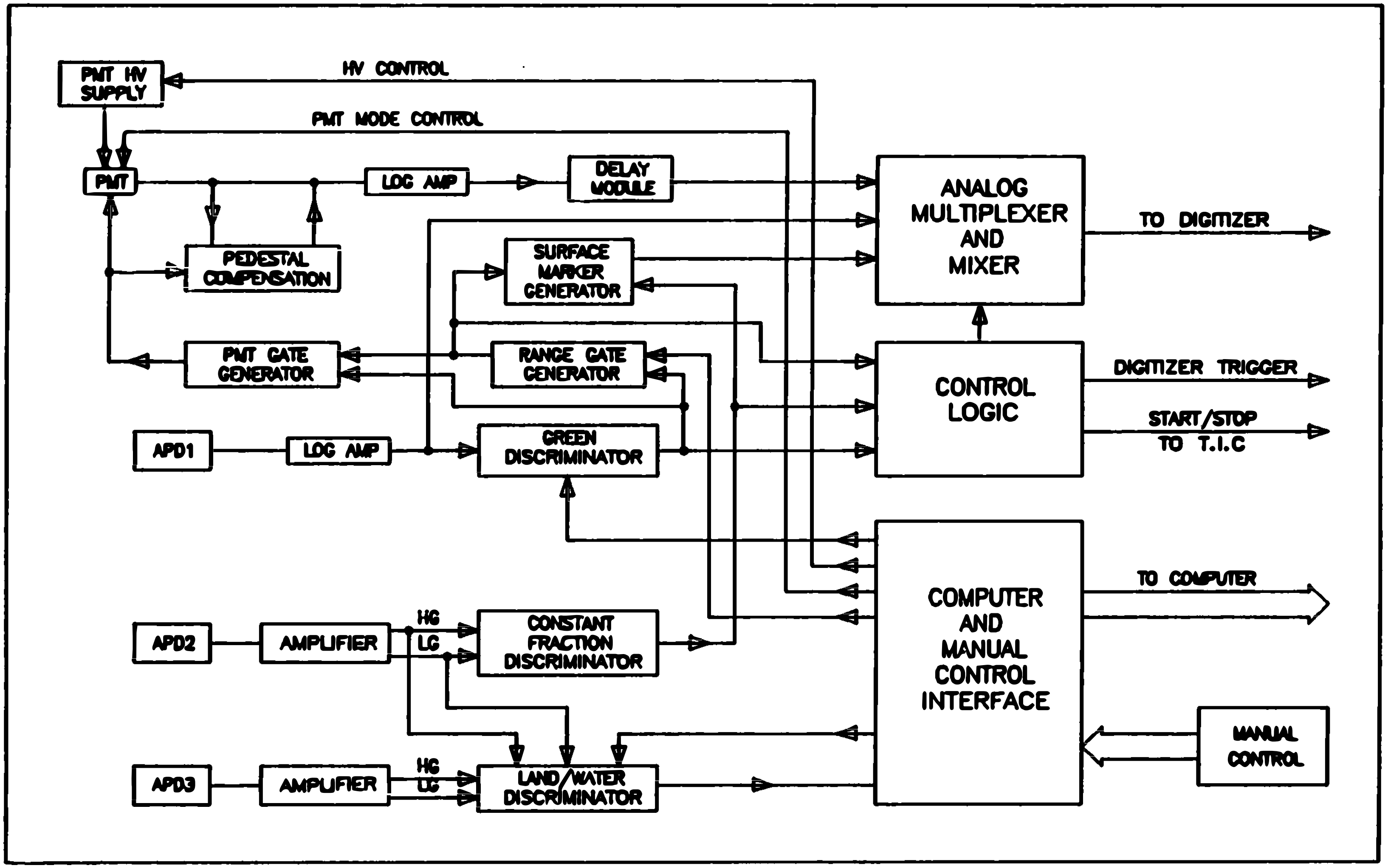


Figure 5-9. Receiver electronics unit

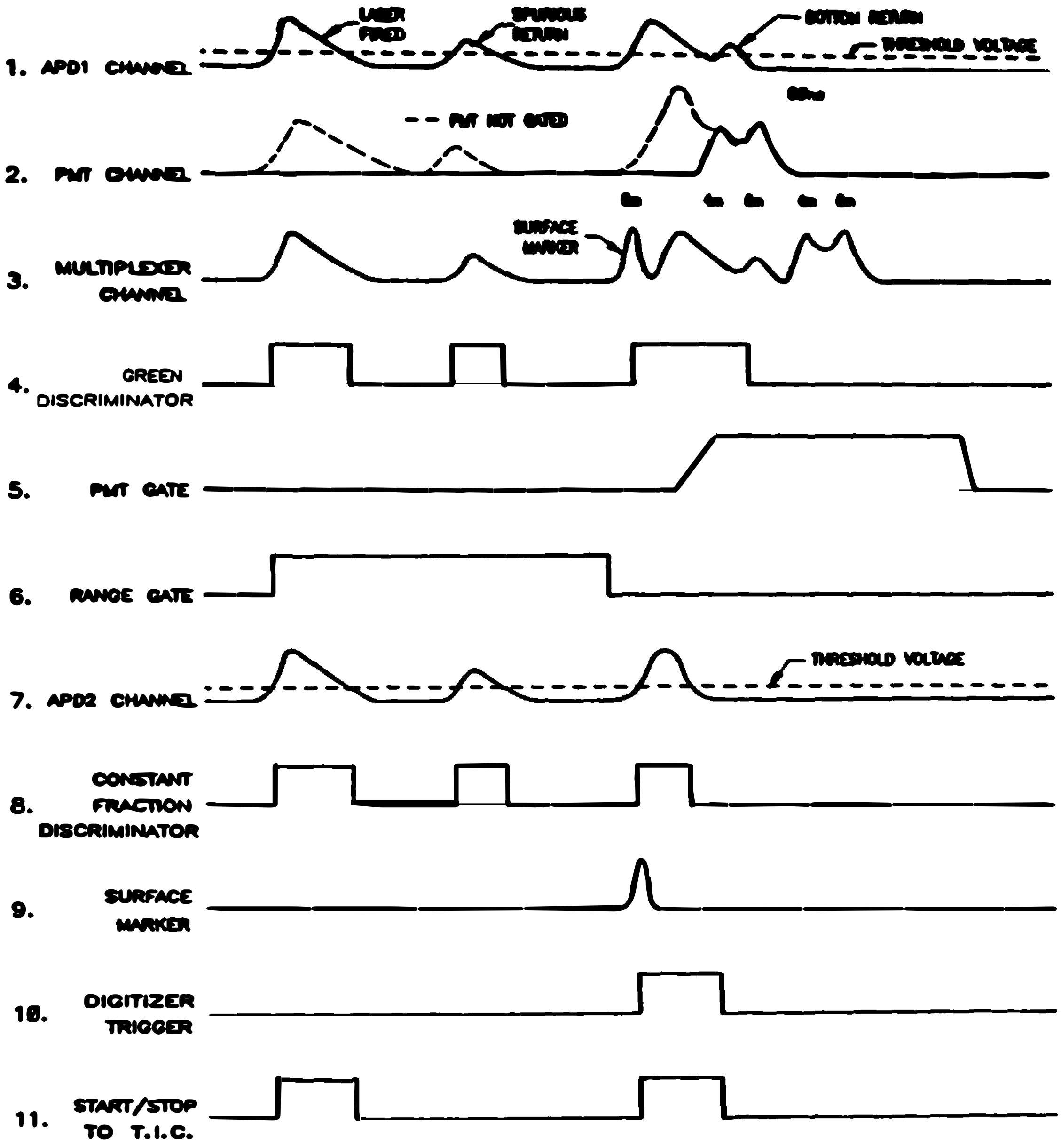


Figure 5-10. Receiver timing diagram

high intensity background light, and the resulting high DC output current from the gated PMT, can result in a loss of dynamic range for the PMT output. A pedestal compensation circuit will be incorporated to eliminate this effect.

The dynamic range of the PMT will be matched to the input range of the digitizer by a custom version of Optech's OS-LA-5-100 logarithmic amplifier; the unit has a dynamic range of almost five decades and a bandwidth of approximately 200 MHz. A delay module will delay the signal from the logarithmic amplifier in the PMT channel, in order to permit the digitization of the shallow water return signal detected by APD1 before the PMT signal arrives.

An avalanche photodiode, APD1, will be used as an additional detector for green radiation from shallow water less than 5 meters deep. The APD1 channel will consist of the APD and a custom version of Optech's logarithmic amplifier.

APD2 and APD3 will detect infrared radiation from the surface, providing the signals necessary to determine its nature and location. The APDs receive equal intensity optical signals. Since a wide dynamic range is required, both to detect weak returns at the low end and to prevent saturation of detectors at the high end, either a logarithmic amplifier or a dual-channel linear amplifier will be used. These amplifiers will split the APD current into a low gain and a high gain channel.

The low and high gain output signals will be processed by a constant fraction discriminator (CFD) and a land/water discriminator. The land/water discriminator will determine the origin of the reflected waveform and produce a status signal.

The CFD will generate start and stop pulses for the time interval counter, based on the laser fired pulse and independent of the amplitude of the return signals. The CFD output will also trigger the surface marker generator, which will produce a reference pulse for the software algorithm determining the water depth.

A green discriminator circuit will produce a pulse whenever the output signal from the APD1 channel exceeds the preset threshold. This pulse will trigger a signal from the range gate generator which will, for its duration, inhibit the recognition of return signals. The output of the range gate, supplied to the surface marker generator, thereby prevents it from triggering on spurious return signals produced by, for example, patches of fog, small clouds or birds.

The receiver control logic will receive logic signals from the CFD, the green discriminator and the range gate generator. It will produce the start and stop pulses for the time interval counter, the digitizer trigger for the digitizer and the select channel signal for the analog multiplexer and mixer (AMM). The AMM arranges the outputs of the PMT and the APD1 channel in areas of data overlap from shallow water returns, and adds the surface marker pulse to the output waveform.

The combined waveform containing subsurface and surface return signals is used to extract the water depth. The output from the three APD channels will also be used to generate the timing and control signals required for proper discrimination and data acquisition.

Some parameters controlling the operation of the receiver electronics will require interactive variability and monitoring, provided by the computer and manual control interface. During operation, the receiver electronics will be strictly computer controlled; manual control, however, will be incorporated for system testing purposes.

5.1.4.1 Real Time Signal Processing

A logarithmic amplifier is required to interface the PMT to the digitizer. It compresses the dynamic range of the output from the PMT into the input dynamic range of the digitizer. The performance of the logarithmic amplifier will be crucial to the depth measurement accuracy of the HLBS. Its performance characteristics are a limiting factor of the maximum detectable depth.

Optech's OS-LA-5-100 wideband logarithmic amplifier (WLA) was designed to fill the gap between conventional logarithmic amplifiers, which are too slow for the HLBS, and detector logarithmic video amplifiers (DLVAs), which are designed to operate at an intermediate frequency and a narrow frequency bandwidth. Its dynamic range covers almost five decades of input signal, and the bandwidth extends from 300 Hz to 100 MHz. The WLA consists of four identical AC-coupled wideband amplifying stages. Each stage has a nominal gain of 15 dB for small signal levels, falling to 0 dB at large signal levels. The cascade of such stages provides a close approximation to a logarithmic characteristic. A very short recovery time, with a low noise figure of less than 8 dB, is achieved through the use of 5-GHz high performance transistors.

For small signals under -80 dB, the WLA will operate as a linear amplifier.

5.1.4.2 Slant Range Time Interval Counter

The slant range to the water or land surface over which the HLBS is operating will be measured by Optech's Time Interval Counter (TIC). This circuit will measure the time delay between a reference pulse, produced at the instant the laser fires, and the reflected infrared laser pulse. Both pulses are normally obtained from the infrared APD channel. However, if the condition of the reflecting surface is such that a signal dropout occurs, the system will automatically use the return signal from the green channel APD. This selection will be done on a pulse-by-pulse basis as a function of the amplitude of the infrared surface return signal.

The TIC will receive its start and stop signals over a 50Ω coaxial cable. These pulses are at fixed (ECL) levels. The output of the TIC is a 19-bit binary word representing the distance to the reflecting surface in centimeters.The TIC has an accuracy of better than ±2 centimeters. The slant range will be read over a parallel port by the computer system after each laser shot.

The TIC can operate in either First or Last Pulse Mode; the former for measuring the range to the closest target and the latter for measuring the range to the furthest target. If low level mists are found to be causing multiple return pulses, the unit will be operated in the Last Pulse Mode even though the accuracy will be slightly degraded to ±3 cm. Spurious reflections from nearby targets will be eliminated by the use of the range gate, which is part of the receiver electronics and controlled by the computer system.

5.1.5 Video Camera

A video camera/recorder will display and store the image of the scanned area. The image will be used by the operator to aid in the interpretation of anomalous data. A video signal, for on-line use with the ground-based processing system, will be supplied for digitization at approximately 1/2 Hz. The camcorder will use the same 8mm format of recording tape used by the airborne data acquisition tape drives. The small and rugged camcorder will record up to two hours with one tape and will be remotely operated.

5.2 Acquisition, Control and Display Subsystem

To perform all the airborne data processing functions, the HLBS will require a powerful computer capable of performing many simultaneous operations. The primary functions of the airborne computer system will be:

1. Acquisition of data from all sensors and the recording of this data for later processing
2. Presentation of data to the system operator in an easy to understand format
3. Production of the displays required to guide the pilot along a pre-determined course
4. Analysis of digitized laser returns to produce a depth value in real-time
5. Analysis of incoming data from all sources, and the production of quality control information for the operator

6. Automatic control of various devices and sensors to achieve optimum performance under changing conditions

7. Manual control of all devices or sensors by the system operator

To meet these requirements it will be necessary to use a computer system containing several processors, each of which will work on one or more tasks. These processors will be linked physically through the system bus, and logically by the use of a multiprocessor operating system.

5.2.1 Data Acquisition

Data acquisition is the most important and fundamental function of the airborne computer system. To ensure the maximum utility and flexibility for the bathymeter, it is necessary to gather and record all potentially useful information available. This will enable post-flight analysis to be as accurate as possible. By capturing every available data item, even those that will not be currently used by the Ground Based Data Processing System (DPS), the ability to re-analyze the data using improved or different techniques will be maintained.

To handle the large (approximately 145,000 bytes/second) stream of data efficiently, each data item will be tagged with a leading byte, which will describe what type of data follows and how many bytes it will occupy. The tagged data will be stored in a temporary buffer in the memory of the data acquisition processor. When the buffer has been filled, it will be written to the tape and a new buffer will be started. To ensure a maximum amount of error-free data, all data blocks will be started with a tag byte. Data blocking in this manner maximizes the amount of data which can be stored on a single tape.

The largest data item on tape will be the digitized waveform. To minimize the amount of bytes required, this data item will be written in a variable length field. On surveys where water clarity or other environmental conditions prevent the detection of bottoms past a given depth, the airborne system will store only the number of bytes necessary to obtain an accurate estimate of the depth. An appropriate safety margin, automatically derived by the system, will be included in the sample. The operator will be able to intervene and adjust the safety margin to suit varying conditions.

The time of each laser pulse will be recorded to an accuracy of one millisecond. This time will then be attached to the digitized underwater signal and to any other data that requires deskewing. The use of fast processors will ensure that all data items are stored within 0.5 milliseconds of their arrival. The digitized underwater signal will be the fastest recurring data source; its data bytes will arrive every five milliseconds. Hence all data occurrence times will be accurately known and can be associated with a specific laser return.

If allowance is made for a few additional data items, the maximum possible data rate will be in excess of 150 Kbytes/second, sustained for periods as long as 2 to 4 hours, depending on the airborne platform.

The tape unit for this application will be a high capacity 8mm cartridge tape system manufactured by EXABYTE. It incorporates a small computer system interface (SCSI) and uses industry standard 8mm tape cartridges which are removable and reusable. Each cartridge can store more than 2,000 MBytes of formatted data, most likely enough for over four hours of data acquisition. An error correction code (ECC) is built in, with the error recovery procedures implemented in the controller hardware. If an error is detected, the tape drive will mark the previously written data as bad and re-write the data in a new area of tape. By using this read-after-write ECC, the tape drive is capable of a non-recoverable error rate of less than one bit in 10^{13}.

To reduce the chance of data loss due to hardware failure, the airborne computer will contain two tape drives. Data will be written to both drives simultaneously during data acquisition, thus producing two copies of the data for ground processing. If there are anomalous or missing data on one tape, the other tape will be used as a backup to recover and replace the bad or missing data. Creating two copies of the tape during the survey mission will also reduce the amount of time spent by the ground system in creating additional copies for distribution or archiving purposes.

5.2.2 Real-Time Displays

The operator interface to the HLBS computer system will allow access to all the information being gathered by the airborne computer system. The operator's real-time display will be a color monitor with 1024 by 1024 pixel resolution capable of displaying up to 256 colours. For data input the operator will have a keyboard and a trackball. A trackball is ideally suited for airborne use because the operator can rest his whole arm on a horizontal surface and manipulate the trackball, along with its buttons, with his fingertips. This requires a minimum of operator movement and is not adversely affected by the movement of the aircraft.

To simplify the operator interface, all information and controls will be presented as a series of menus and windows. The operator will use the track ball to select the main menu listing of the windows. Those currently active or unavailable will be highlighted. To select a different function or display, the operator will move the cursor over the desired menu item and press a button on the trackball. By arranging all operator actions in a hierarchy, it will be possible to use the trackball, instead of the keyboard, almost exclusively while the HLBS is airborne. This windowing technique will allow the operator to display only the information required for a particular survey. All other information will be available through the use of additional windows or menus.

Depending on the requirements of the survey, certain menu selections, though displayed for reference, will be locked out. For example, the operator will not be able to change beam divergence to a value lower than the eye-safe level while in the air. The other possible choices will still appear but will not be selectable at that time.

The largest portion of the operator monitor will be dedicated to a display of colour-coded depths in real time. Depth values will be the most completely processed form of data and, as such, will indicate the most about the functioning of the system. The real-time depth display will take the raw depths and aircraft location, and then correct for such factors as pitch, roll, and heading. The result of the corrections will be a scaled XY co-ordinate value, with a corresponding colour-code for depth. This may be displayed as a pixel, group of pixels or number, depending on scale, in the depth display window. A number of proven hydrographic criteria can be used on such a display to provide a reasonably reliable indication of the data quality.

The depth display will operate in one of two modes. In the first, the depth window will show a large portion of the survey area with the calculated depths shown as colour codes. New depths will be added at XY locations on the display, thus marking the progress of the aircraft within the displayed area. The display will automatically pan or scroll if the aircraft flies out of the displayed region. The operator will be able to 'zoom-in' on a particular area to examine individual depths. In addition, any available coastline and navigation information will be displayed as an indicator of positional accuracy.

In the second mode, the depth display will appear as a downward scrolling image in a window width equivalent to one scan swath. As the aircraft flies, the display will scroll downwards at a rate proportional to the aircraft velocity, with the latest acquired depths at the front of the scan appearing at the top of the display. Again,-the operator will be able to zoom in to examine a particular region of interest. In both display modes, those returns falling on land will be specifically indicated. Areas where the depth could not be calculated for other reasons will be left blank. In the latter mode, the operator will also be able to superimpose the colour-coded depth display on the black-and-white image from the down-looking camera. This will enable a spatial correlation of the colour depth display with any geographical and environmental features, and thus facilitate the interpretation of data anomalies.

The depth display window will also give a good indication of the completeness of area coverage by showing any gaps between adjacent flightlines. A sample of the operator's display is shown in Figure 5-11. In this figure the operator has selected the overview mode of the depth display and activated several other windows for additional information. Additional information can be called up through additional windows, which the operator will be able to place anywhere available on the display.

5.2.3 Pilot Guidance

The pilot guidance subsystem will facilitate the hydrographer's direction of the airborne survey operation, and enable the pilot to manage the flight lines. The pilot will be able to select one of two guidance displays for presentation on the monitor. One display will present a digitized map of the survey area. A marker indicating the aircraft's current position will be superimposed on the map. The marker will be updated at a minimum rate of 5 Hz, permitting the pilot to determine his position accurately at any time during the survey mission. The second display will indicate the relative position of the aircraft with respect to the flightline. The pilot will use this display to keep the aircraft on the flightline to be navigated.

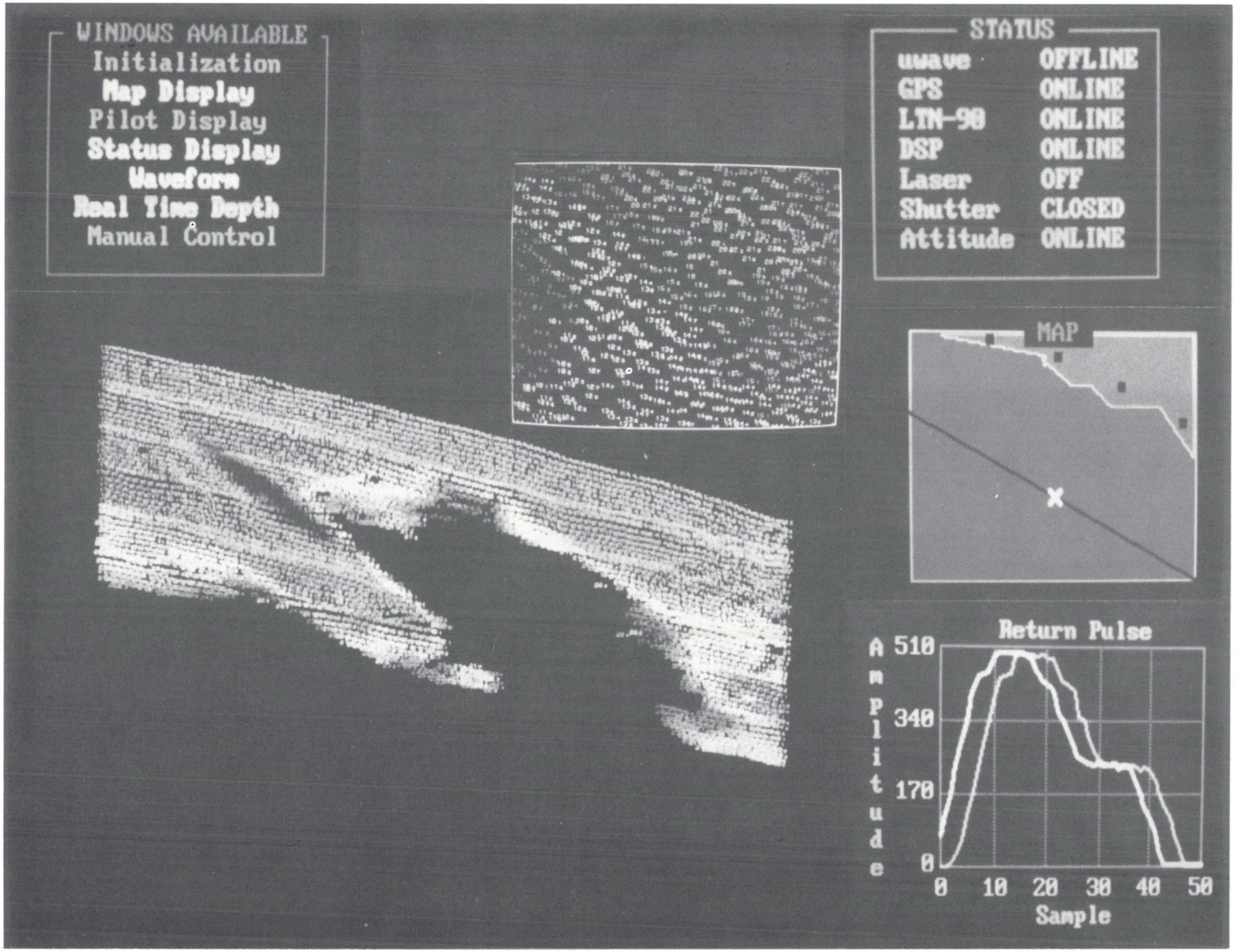
The guidance system will be equipped with pre-flight software to facilitate the selection of the survey parameters. The hydrographer will evaluate the most effective way of covering the desired survey area and prepare the flight plan to be followed during the survey. A suitable interface will facilitate the uploading of this pre-flight digitized map and flight-line information from the ground-based system onto the airborne computer system.

The airborne computer will acquire all the parameters needed to update the pilot guidance displays from the various positioning sensors. The flight parameters required will include aircraft position (corrected latitude and longitude), altitude, track angle, heading, and map and flightline information.

The altitude of the aircraft will be determined from the slant range and corrected in real-time with respect to scan angle and aircraft roll and pitch. Aircraft track and heading will be obtained from the inertial reference system.

5.2.3.1 Displays

The pilot display monitor in the cockpit will present two possible screens for selection by the pilot. One of the displays will show a digitized map of the area to be surveyed. A typical map display is presented in Figure 5-12.



STATUS
uwave OFFLINE
GPS ONLINE
LTN-90 ONLINE
DSP ONLINE
Laser OFF
Shutter CLOSED
Attitude ONLINE

Figure 5-11. Sample of operator's display

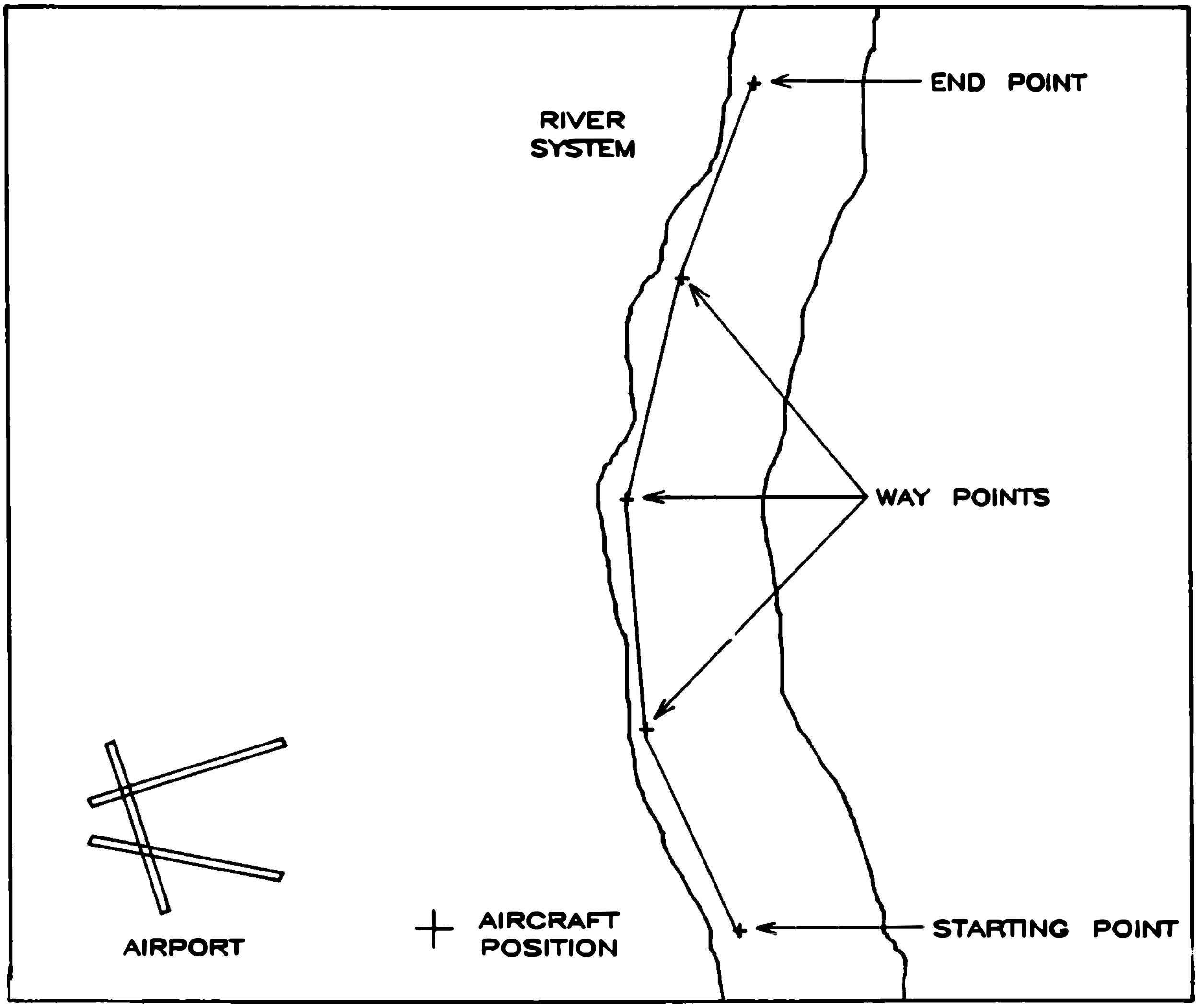


Figure 5-12. Typical map display

This map display will present the locations of each flightline as they are to be flown, and will also present a record of the track flown by the aircraft. Once the aircraft is within the area covered by the map, a marker indicating the aircraft's position will appear on the screen. The pilot will use this screen to align the aircraft with the flightline. If the initial location of the aircraft is not within the range of the map, the marker will remain at the edge of the display screen.

The second display will indicate the aircraft's altitude, the distance of the aircraft from the flightline (the cross-track error), and the track angle error. The aircraft's altitude will be indicated on a vertical scale on the left of the display. Cross-track error will be shown on a logarithmic scale across the top of the screen. A vertical bar at the bottom of the scale will indicate current cross-track error.

A line display, including an aircraft symbol, will occupy the center portion of the screen. The line drawn will represent the desired flightline and show the aircraft's position relative to the flight line. The angle of the line will represent an unscaled cross-track angle error; the distance from the line will indicate the logarithmically-scaled distance from the flightline. If the line is more than 500 meters from the aircraft, the flightline will appear at the edge of the screen. A typical map display is presented in Figure 5-13.

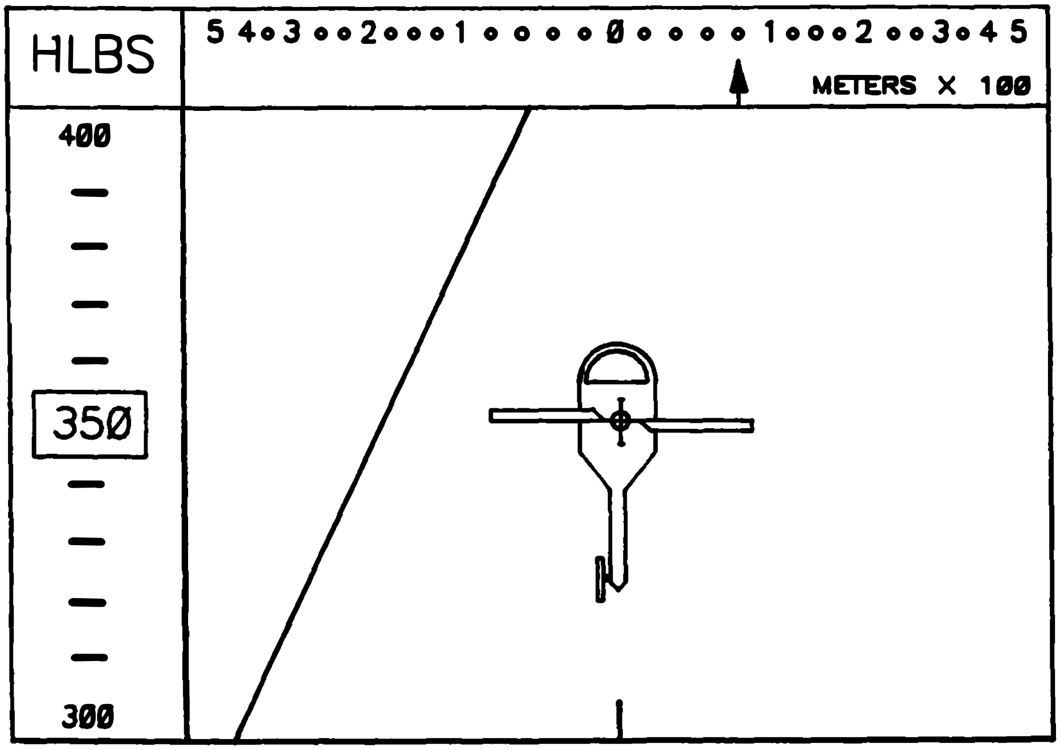


Figure 5-13. Typical pilot guidance display

5.2.3.2 Software

The pilot guidance software will comprise three pre-flight software modules, assisting the hydrographer with survey planning, map digitization and flightline planning. This software will be available on both the ground-based DPS and the airborne computer system.

The survey planning software module will enable the hydrographer to determine the optimal laser shot spacing and flightline overlap. Parameters including aircraft velocity, altitude, scan angle increment per laser shot, and scanner speed may be varied. By selecting the parameters in their order of priority, the hydrographer will be prompted by the computer through a sequence that will optimally determine the values of such parameters for that mission.

The map digitization software module will produce an on-line map of the area to be surveyed. A detailed map must be available with at least two known grid co-ordinates and a central meridian of the zone in which the survey area lies. This map will be digitized by a digitizing tablet interfaced to either the analysis or airborne computer systems. All shorelines, landmarks and other noteworthy reference points helpful to the pilot should also be digitized. If the map is digitized on the data-processing system, the file generated will be downloaded on to 8mm tape, for uploading onto the main airborne system.

The third module will be used by the hydrographer to input the actual flight lines. The hydrographer will select the beginning and end co-ordinates of the flightline, as well as any intermediate points (waypoints), if the flight line is to follow a special geometric path. The hydrographer will be able to select the distance between flightlines. Figure 5-12 illustrates typical flight lines as they would appear on a map display.

5.2.4 Depth Extraction

An important feature of the HLBS airborne computer system will be its ability to calculate water depths in real-time for airborne display and recording purposes. The calculated depths will be used by the system to generate a colour-coded display of the bottom topography, providing the operator with a tool to assess the quality of the bathymetric data as it is being gathered. The constraint on the processing time available in the air will limit the maximum depth calculation rate to a value less than the full 200 Hz laser firing rate if high accuracy depth data is needed. A likely choice may be a combination of low density, highly accurate depths with high density, lower accuracy depths.

The extraction of depth data from the lidar waveforms will be implemented in software, which provides the flexibility necessary for the optimized function on the display.

5.2.5 Quality Control

To minimize the likelihood of data loss, the airborne computer system will have extensive quality control features designed into both the hardware and the software.

The latest generation of processor and interface cards have a variety of quality control features including varied diagnostics and error reporting, as well as the ability to isolate faulty boards from the bus to prevent computer lock-up. The computer will automatically re-distribute tasks among the remaining boards so that data processing and control can continue without interruption. If a card must be replaced for computer operations to continue, the operator will be alerted to the fault through the operator display and diagnostic lights on the system.

Several software tasks will be dedicated to monitoring the performance of all equipment connected to the computer and alerting the operator if problems are detected. The quality control software will also monitor the data and flag readings when values are outside pre-determined boundaries.

All status information will be summarized for the operator and used to generate a flag for a particular device or process. If all operating conditions are within specifications, a 'GOOD' indication will be displayed on the monitor.

5.2.6. System Control

The HLBS system will be designed for control by one operator. From the initial set of data input by the operator, the computer will calculate optimum settings for all the equipment it will be programmed to control, and adjust settings as required.

Computer control will be designed to enable the system to recognize unsafe operating conditions and take the necessary corrective action to prevent damage to the system or possible injury to personnel. This is an area where fast electronic response time is especially critical.

Although the system will be able to control all major aspects of system operation, the operator will be able to intervene manually through the monitor and keyboard. By proper menu selection the operator will always be able to read the current status and settings of the device being controlled. This will allow the operator to verify that any manually requested changes have been made and that the device is functioning properly.

Even when a device is under the operator's manual control, the airborne computer system will ensure that the device is being operated safely. The computer will not allow any parameter choices that may lead to equipment damage or unsafe conditions for personnel. A list of safe operating ranges for all systems will be displayed in an appropriate menu on the monitor. During system testing, however, the computer-set ranges may be by-passed using techniques available only to specially trained personnel.

5.2.7. Computer Hardware and Software Architecture

5.2.7.1 Hardware

A high power multi-tasking computer will be required to accomplish the processing. The workload will be divided among several processors, each dedicated to one large task or a number of smaller tasks. A multi-processor bus architecture is therefore required.

The VME bus chosen for the HLBS is a 32-bit bus with a usable bandwidth of 10 MHz. Cards for the VME bus come in pre-defined Eurocard sizes and are connected to the backplane by pin connections; card edge connectors are not used. This will increase the reliability of connections under the conditions of airborne operation.

The VME bus is a widely supported and available system architecture. It defines additional auxiliary buses for high-speed data transfer from card to card within the backplane. Auxiliary buses may be used to capture the digitized lidar waveforms and move the data from processor to processor within the computer system.

5.2.7.2 Operating System

The design of the airborne computer system will require a real-time operating system permitting rapid and efficient interaction between multiple processors. To develop the necessary software quickly, the operating system must have a superior development and debugging environment.

Multiprocessor Toolsmith's UNISON will be the operating system used with the HLBS. It is capable of managing multiple tasks in a real-time environment and executing the task of highest priority. Its development environment allows rapid debugging.

5.2.7.3 Software and Software Development

The software for the HLBS system will be written in the 'C' programming language. 'C' is a highly structured, general purpose language which readily lends itself to a real-time environment. It is very portable and works on almost all types of hardware with minimal modifications. 'C' also provides a rich set of operators with an economy of expression and little overhead. It is one of the most widely accepted and used programming languages, with a structure which makes it ideal for multi-user development.

All software will be task-oriented. These tasks will be structured and modular, executable on any one of several processors. Tasks will interact and communicate between themselves. The real-time operating system will control all task communication and synchronization.

The development environment will be based on Multiprocessor Toolsmiths REMEDY, designed as the development tool for the UNISON real-time operating system. UNISON and REMEDY are designed to work on SUN hardware, providing a multi-user, multi-tasking environment that greatly increases productivity.

5.2.7.4 Computer Enclosure

All processor and interface cards required for the airborne computer will be housed in a single standard 19" rack-mountable enclosure, 15.75" high and 24" deep, including space required for cables and connectors. This chassis will accomodate up to 20 VME cards, two helical-scan tape drives, and battery backup. The chassis will be air-cooled and ruggedized for operating in the airborne environment.

The chassis will operate at +28 VDC or 110 VAC (40-400 Hz), permitting incorporation into virtually any airframe with minimal modifications to existing power distribution systems.

It will weigh approximately 75 pounds and require a maximum of 500 watts.. Its battery backup will allow the system to survive power fluctuations when switching to and from ground power.

5.2.8 Digitizer

The digitizer recommended for this application is Analytech's Model 2004SH. This model, currently under development, is an expanded version of the standard Model 2004S with extra circuitry and improved data throughput. It consists of a set of VME boards comprising a sampling board, timing board and accelerator board. The sampling board has four digitizing channels, each capable of 500 Msamples/second single shot. Two channels will be interleaved by an external adapter to provide 1 Gsample/second.

The Model 2004SH has 10-bit resolution and an input bandwidth of 280 MHz. It can store 4096 samples when operating in the two-channel 1-Gsample/second mode. Corrections to the raw digitized data, which are required to achieve the quoted specifications of the unit, are performed in hardware by the accelerator board.

To record waveforms from the maximum depths anticipated for the HLBS, an acquisition memory of 512 words will be used. Since one meter of water depth corresponds to 8.9 ns of transit time, 512 samples at 1-ns intervals will enable waveforms to be captured from water up to 57.5 meters deep.

The cycle rate of the Model 2004SH will be greater than 2 kHz, well above the laser's 200 Hz repetition rate. Since both the digitizer and the airborne computer system are based on the VME bus, communication between these devices will be relatively straightforward.

5.2.9 System Implementation

Figure 5-14 presents a conceptual representation of a likely implementation of the design of the airborne computer system. This configuration requires thirteen VME bus slots and contains four main processors, one each for depth extraction, data acquisition, quality control/operator interface and navigation. In addition, a number of the other interface boards contain processors to offload the four main processors. All processors will work in concert under a real-time operating system. There is ample room to install additional cards to receive or process any additional future data.

This configuration will use the VSB auxiliary bus to transfer the digitized waveforms within the system, with the main VME bus being used for all other communication and data transfers. This design approach would avoid possible bus timing problems caused by all data passing only through the VME bus.

5.3 Positioning System

To obtain the real-time position of the helicopter, either a microwave positioning system or a Global Positioning System (GPS) will be used. The airborne computer will have the ability to interface to either system.

A GPS system is preferred because of its ease of use. However, until a full constellation of satellites has been launched, its use may be limited to an undesirably low number of operating hours each day. The GPS will be used in a differential mode with a ground-based GPS receiver located at a known surveyed point. The preferred method is to transmit data over a radio frequency link to a GPS receiver on the helicopter. If this is not practical, a ground-based data logger will be used.

In a real-time, differential, dynamic mode, the accuracy is typically from two to five meters (SEP). This assumes that the receiver is using the C/A code available to civilian users. However, it must be noted that for the Block 2 satellites, the US Air Force may limit accuracy to 100 meters. Block 1 satellites will continue to provide better performance as long as they remain operational.

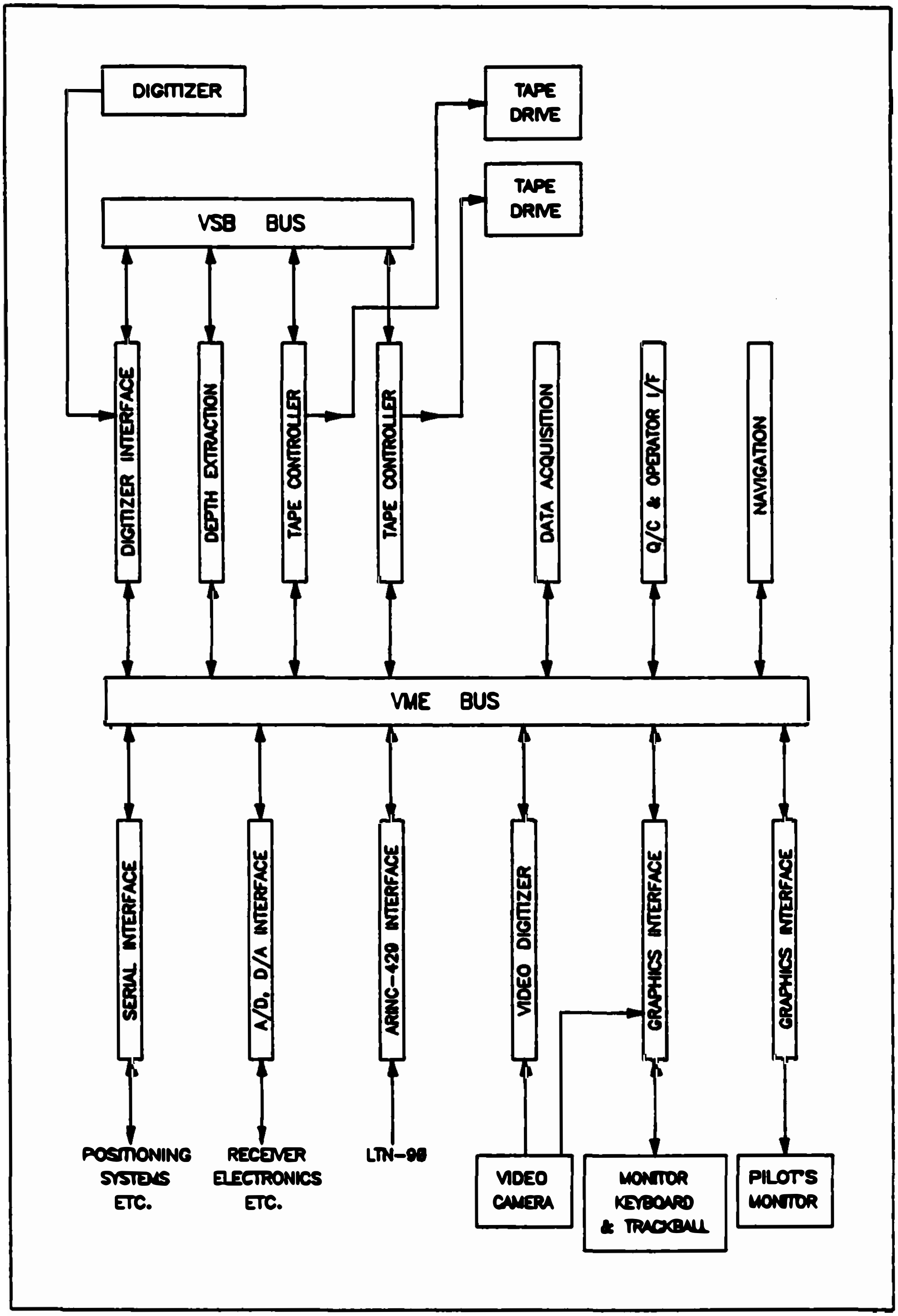


Figure 5-14. Airborne computer conceptual design

A variety of C/A-code receivers are on the market. In a dynamic environment, a receiver that can simultaneously track at least 4 satellites (i.e. a 4-channel receiver) is considered preferable to a single-channel sequencing receiver. Likely candidates for the GPS system are the 4-channel Motorola Eagle or the 5-channel (expandable to 7 channels) Norstar 1000. Position updates will be provided on an RS232 port at a rate of 1 Hz.

In the near term the microwave positioning system will be used. In order to minimize the probability of signal dropouts, it is desirable to deploy at least eight transponders. The system must be capable of selecting any four from which to obtain a position fix. Likely candidates for this system are Motorola's Falcon Mini-Ranger, or the Del Norte Trisponder System. Typically, in an operational scenario, a range accuracy of 1 to 4 meters can be achieved. If the system is operating over sea water, accurate altitude measurements can be obtained from the slant range measurements.

The antenna for the aircraft positioning system will be mounted on the helicopter. Tests on GPS systems have shown that the shielding effect of the aircraft and rotors will be minimal.

5.3.1 Inertial Reference System

The HLBS will use the Litton LTN-90 inertial reference system to measure the attitude angles of the lidar sensor and to provide vertical acceleration data. The LTN-90 can also provide navigation data which may be useful in extending the position information provided by the positioning systems. The LTN-90 will be hardmounted on the lidar sensor to provide a precise measure of its orientation.

The required attitude angles are roll, pitch and heading. This information will be used, in conjunction with the scan angle, to determine the horizontal co-ordinates of the laser spots on the survey surface relative to the aircraft. The vertical acceleration data will be used in the wave-height analysis to decouple aircraft altitude motion in the case of long-wavelength swell.

The inertial reference system will provide digital outputs of attitude, heading, position, angular rates, linear accelerations in body and local-level co-ordinates, ground speed and track, horizontal and vertical velocity components, drift angle and flight path angle. The digital outputs are provided on three identical ARINC 429 high-speed transmitter buses. The system provides 15 significant bits for each of these parameters, and 20 bits for both the latitude and longitude. This results in a resolution of 0.005 degrees for the roll, pitch and heading angles. The quoted accuracy for these parameters is 0.05 degrees for roll and pitch, and 0.4 degrees for heading.

5.4 Ground-Based Data Processing System

The HLBS will acquire up to 200 soundings per second. Each sounding will generate 500 to 700 bytes of data. This represents a very large volume of data in a very short period of time. Advanced software and state-of-the-art processing power will be required to handle this data efficiently and process it quickly. The data processing system will therefore perform the following main functions:

1. Read data collected from 8 mm tape by the airborne computer
2. Determine the depth of lidar soundings from the raw data
3. Calculate the absolute position of each sounding
4. Perform the required set of corrections to the data
5. Allow for editing, plotting and quality checking of the lidar data at appropriate stages of the analysis
6. Provide the final lidar data in a fully corrected digital XYZ database along with the hydrographic data necessary for further analysis by the hydrographer

The data processing hardware will be based on the SUN-4 Supercomputing Workstation, which utilizes the SUN's Scalable Processor Architecture (SPARC) microprocessor. The system will be configured with two gigabytes of disk storage, a 19-inch high-resolution colour monitor, a mouse, a plotter, an 8mm helical tape drive and a cartridge tape drive.

The lidar sounding data will pass through three phases of data processing, referred to as Phase I, Phase II and Phase III, which will take it from an initial raw tape format to a final XYZ database format. As the data progresses through each of these phases, waveform information will be analyzed, auxiliary status data processed and quality control implemented. Status reports may also be generated and editing techniques, both automated and manual, performed. The data flow is summarized in Figure 5-15.

5.4.1 Automated Editing Options

The operator may select some automated editing options during the transfer of data from tape to disk and/or later on during manual editing.

To generate an optimum daily database in an acceptable period of processing time, it is recommended that editing options be exercised as early in the data processing cycle as possible. Some options will reduce processing; other options will reduce the amount of data in the database. Table 5-2 lists a suggested set of automated editing options, which may be exercised at various times during the data processing.

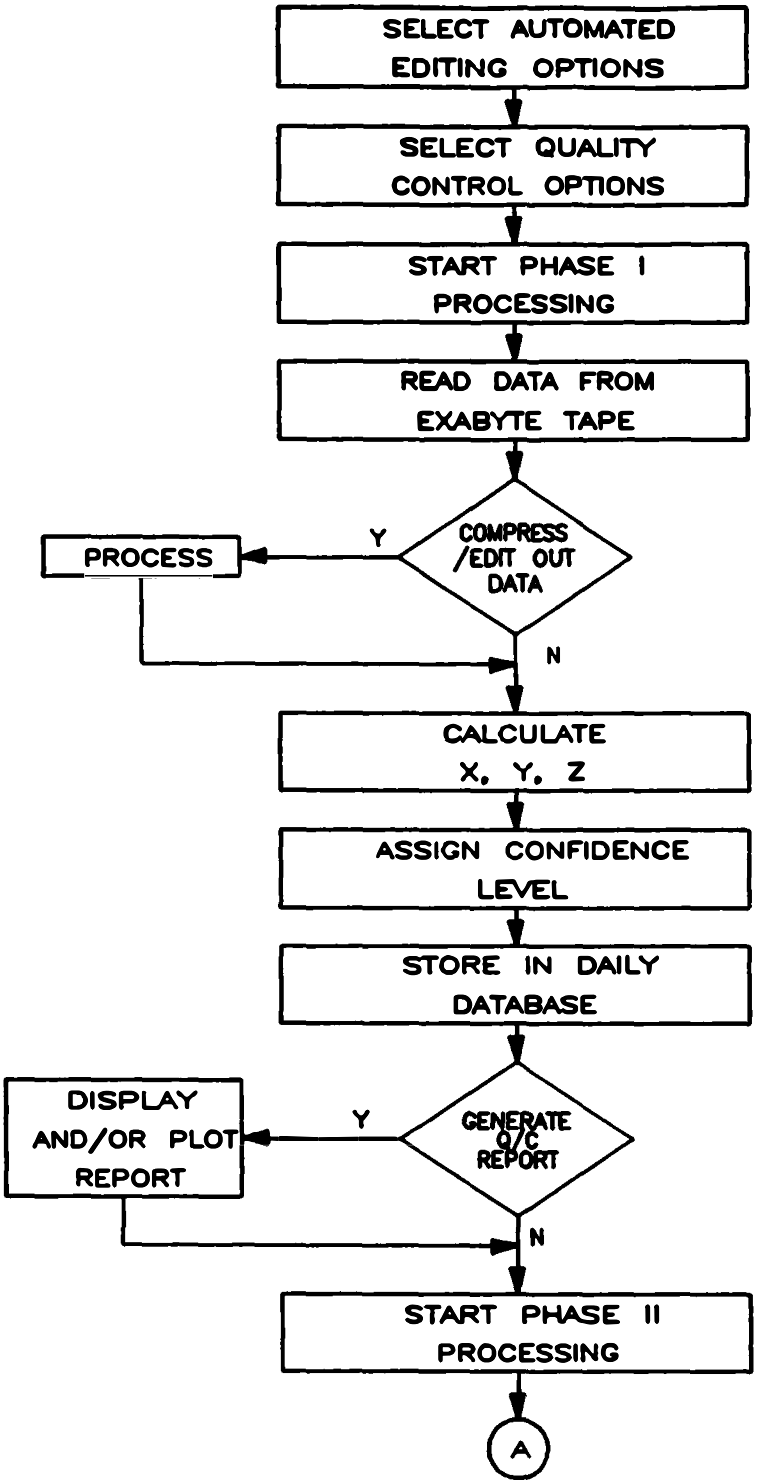


Figure 5-15. Data flow diagram (Continued)

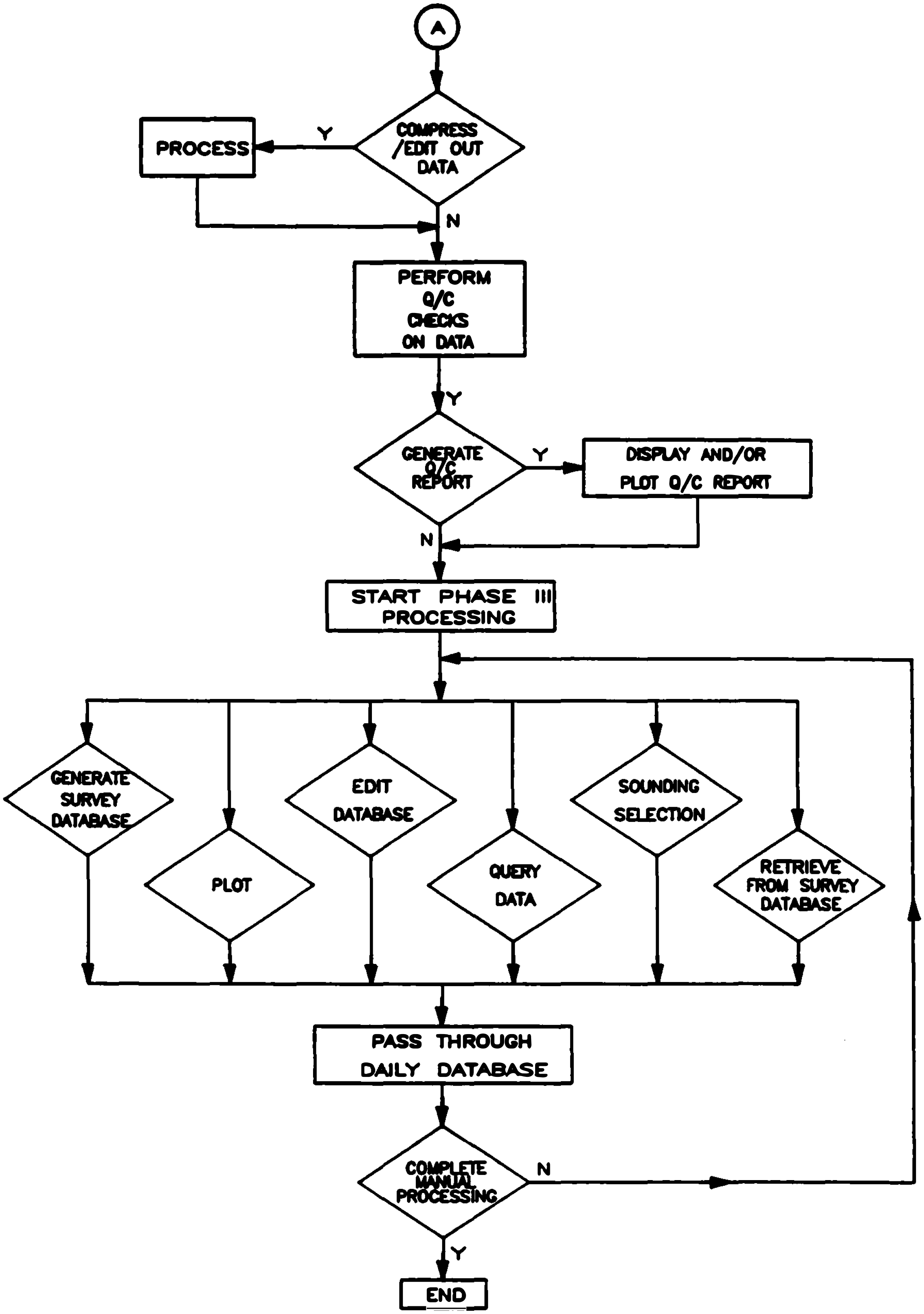


Figure 5-15. (Concluded)

Table 5-2
Automated Editing Options

1. Edit out all data related to a shot with no identified bottom return
2. Edit data to achieve a specific data density, saving shoals
3. Edit out all data related to a land return
4. Edit out waveform data associated with a specific confidence range

Option one would permit the operator to compress certain types of data sets. For example, water that is too deep, too shallow, or too turbid may produce data with no identified bottom returns. The depth detection algorithm will, however, identify and record such a situation. In such a case, the need to store the entire waveform may be deemed unnecessary. As lidar waveforms account for up to two thirds of the the total data, storage space, as well as processing time, can be considerably reduced by compressing such data sets into fewer bytes.

Option two will eliminate soundings, based on grid spacings selected by the operator before Phase I processing. During its implementation, the system will look at adjacent sounding positions in order to reduce their density. This will be done only after the data have been transferred to the daily database at the end of Phase I processing, and the appropriate corrections have been made. This option will not edit out data in shoal areas.

Option three will edit data being transferred from tape. Each waveform will be tagged with a land or water flag at the time of acquisition. The system will read the land/water flag data bit, and only water returns will be written to the daily database.

As a result of Phase I processing, confidence levels will be assigned to each sounding. Option four will eliminate reading into the daily database those waveform data associated with a certain confidence level or range selected by the operator, thus reducing the amount of data stored in the daily database. This option will typically be chosen and applied to all soundings that have a relatively high level of confidence, where the likelihood of examining the raw waveform data at a later stage is low.

5.4.2 Quality Control

Airborne quality control checks will ensure that no required data is missing during acquisition, and that all data have been recorded on tape. The ground-based quality control will monitor the parameters of various system sensors, such as pitch, roll and position, for inconsistencies, and establish confidence levels for the computed depths and positions. Validity checks will be done on the data and erratic data will be eliminated and/or flagged. Quality control procedures will be implemented automatically during Phase I and II processing. During Phase III, quality control will be implemented by the operator.

Optional reports can be generated at various stages of processing and presented to the operator in summary text and/or in graphical form. This report could provide, among other things, a summary of the data confidence levels calculated at each stage of the processing.

5.4.3 Phase I Processing

The primary functions of Phase I processing will be to transfer data from the airborne tape to the DPS, calculate an XYZ for each sounding and store this information in a daily database. The raw data read from tape will consist of digital waveform data, other transceiver data associated with the waveform, and data from the various sensors of the airborne system associated with that waveform. Optional data editing, performed in parallel with the processing, will optimize the processing cycle and the amount of disk space used. These options will be available for selection before running Phase I processing.

In order to maximize the use of the processor, as much processing as possible will be done on the data as it is read from tape. Phase I processing will start with an assessment of the raw data. The most time-consuming task of Phase I will be calculating the depth from each waveform. A confidence level is then associated with each calculated depth and the various corrections to that depth. This will be followed by the calculation of the position of each lidar sounding and the calculation of a confidence level for each determined position.

After completion of Phase I an optional status report will be generated, summarizing the results of the quality control checks performed on the data during Phase I. It will provide information on the confidence levels for all waveforms and a summary of the validity checks performed on the data. Hardcopies of this report will be produced. A summary of Phase I processing is presented in Figure 5-16.

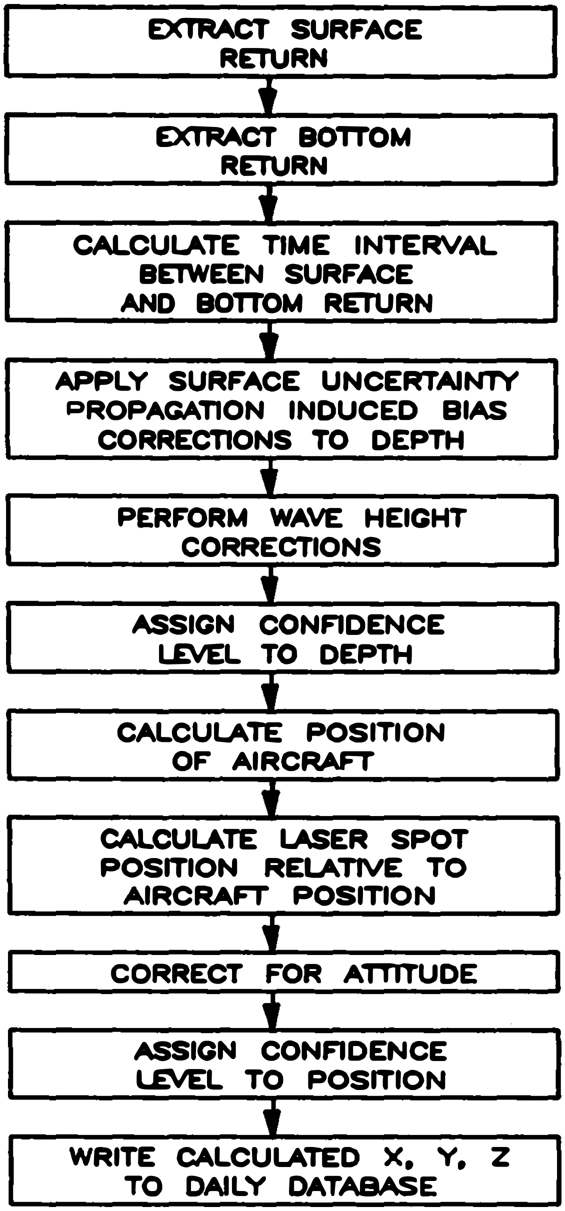


Figure 5-16. Phase I processing summary

5.4.4 Phase II Processing

The objective of Phase II processing will be to geometrically edit and flag data anomalies. Phase II processing will be able to compare associated data in the database. Three-dimensional coordinates will be analyzed and compared to nearby coordinates in an effort to improve the confidence levels of depth and position values. This automated approach will result in less subsequent manual editing. A summary of the data processing during Phase II is presented in Figure 5-17.

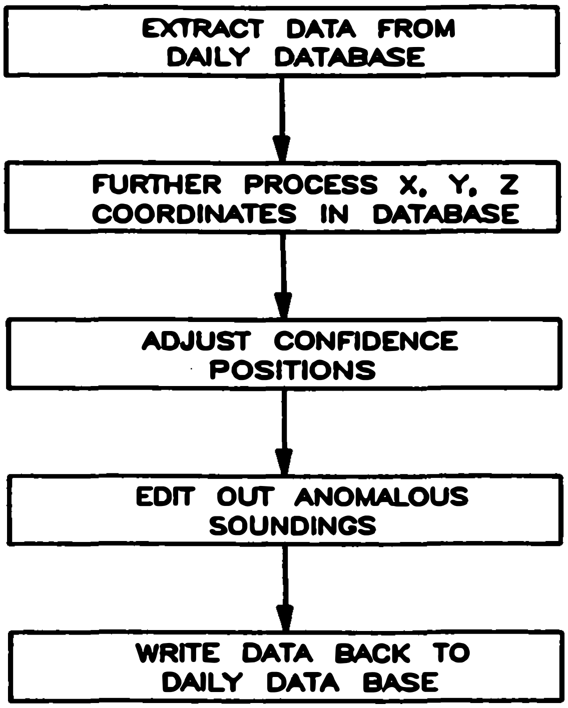


Figure 5-17. Phase II processing summary

5.4.5 Phase III Processing

During Phase III processing, the operator will carry out final data editing. This will involve viewing a graphics display with current and historical information from the database. Phase III activities are summarized in Figure 5-18.

The main objective of Phase III is to make decisions on data anomalies that could not be automatically evaluated during Phase II. During this phase, the operator will also be able to make sounding selections. These activities will reduce the database to a manageable and representative subset of the lidar soundings.

A status report or sounding plot, indicating the level of manual editing required, may be produced at the completion of Phase II. Figure 5-19 presents a typical lidar sounding plot. High-speed editing features will reduce the time required for manual editing. Various display and plotting options will be used to analyze the areas of special interest identified from the sounding plot.

The operator will initiate the data processing functions of Phase III by selecting an area of the database to edit. A Display Option will then be selected from a Query and Display Menu. Each display option will enable quick searches of the data base in areas where data anomalies may be encountered. The sounding display, which consists of a colour-coded depth display of a given area, will also be used to search for anomalous soundings.

Once a selection has been made and a display is available on the screen, the operator will use the Zoom, Pan and Scroll functions of the workstation to examine more of the soundings in the area of highlighted data, or simply to expand the display. The operator will then be able to select an individual sounding and display the information from its database. The video record of the survey mission, the digitized shoreline plot and the waveform of the sounding may also be displayed.

The operator will be able to add, change and delete information from the database by using a series of screens to provide all information about a sounding. A separate Automated Editing and Sounding Selection Menu will provide another opportunity to select the options not chosen at the beginning of Phase I processing. Data not earlier selected from the airborne tapes may be reselected if needed for confirmation during Phase III.

The operator will also be able to review the accomplishments of an editing session and the progress of data quality assurance. An option to calculate the percentage of soundings within confidence ranges will confirm the new data quality.

A backup of the daily database will be made to a tape for archiving when the editing on the daily database is complete, or whenever significant effort has been expended. The final survey database will be updated with XYZ and other final parameters from the fully qualified daily database. The operator will then be able to choose the set of co-ordinates required to meet survey specifications by, for example, selecting grids of a specific spacing for the area. The final output of the sounding selection will be merged with the survey database.

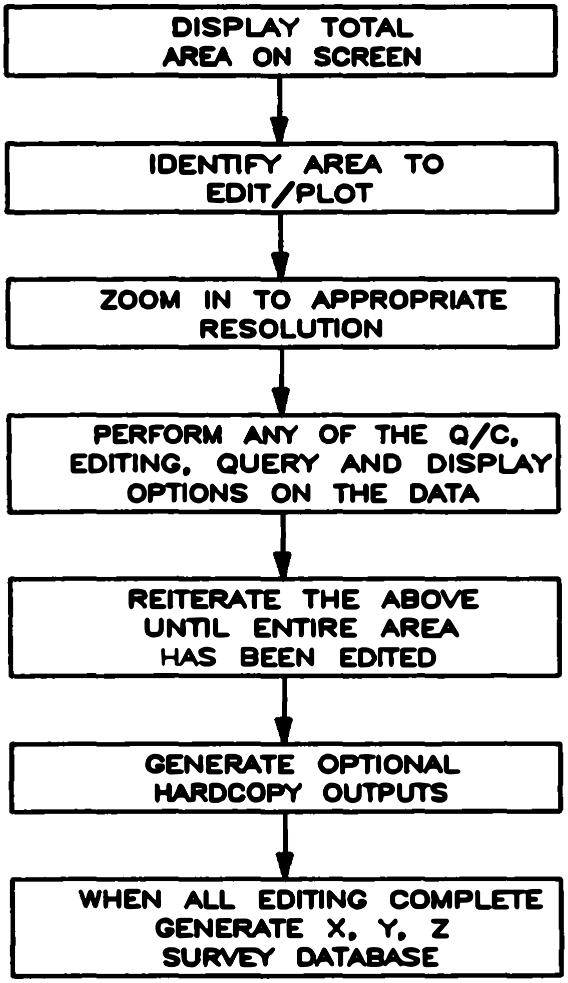


Figure 5-18. Phase III processing summary

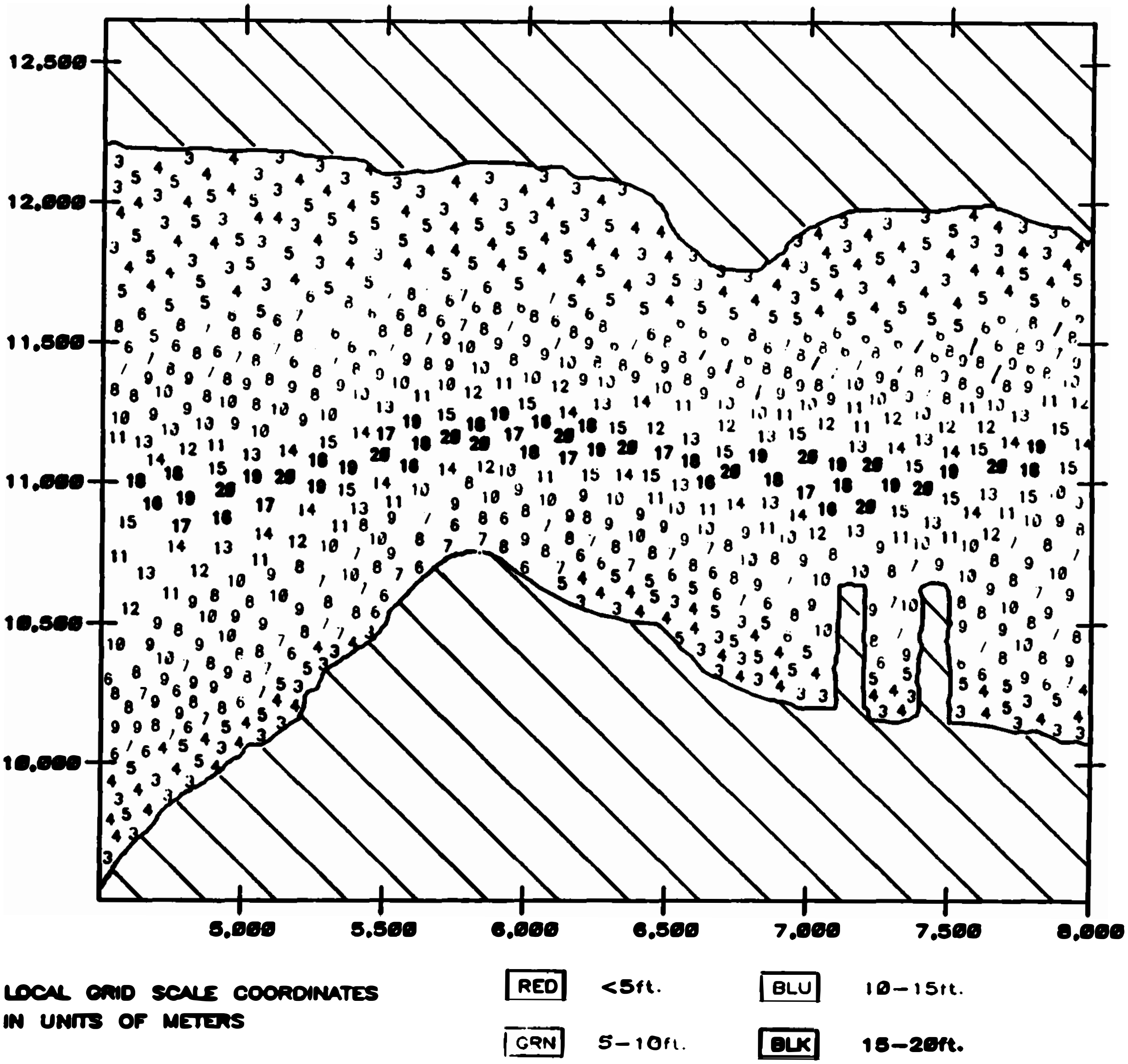


Figure 5-19. Typical lidar sounding plot

5.4.6 Waveform Analysis

The objective of waveform analysis is to have the selected algorithm reliably identify the surface and bottom events. The algorithm must therefore discriminate between spurious signals and noise by evaluating both signal amplitudes and risetimes. Bottom events, once identified, will be time-tagged. The depth will be calculated and then corrected for bias errors caused by surface uncertainty and propagation-induced path length variations.

The waveform analysis algorithm will perform the following steps:

1. Detect the surface return and associate a unique time with its arrival
2. Detect the bottom return and associate a unique time with its arrival
3. Estimate the diffuse attenuation coefficient (k) of the water column, its figure of merit, and the running averages of those quantities used for the processing of subsequent pulses
4. Calculate the depth based on the time interval between surface and bottom returns and apply bias corrections
5. Generate an indicator of confidence level for the determined depth

5.4.7 Hardware Description

Survey data will be processed in the DPS by a SUN-4 Supercomputing Workstation incorporating the SUN Scalable Processor Architecture (SPARC) microprocessor. This microprocessor is built around a Reduced Instruction Set Computer (RISC). The RISC architecture outperforms processors of conventional design by eliminating less frequently used complex instructions, thus enabling the average instruction to execute in fewer clock cycles and leading to an increase in the system's overall performance. At the time of writing over 10 models of the SUN-4 workstation were available, with the fastest being the SUN 4/490. This workstation is rated at 22.5 Million Instructions Per Second (MIPS) and can accomodate up to 640 megabytes of RAM and over 32 gigabytes of disk.

Benchmark studies with the proposed lidar waveform processing algorithms indicate that a single 30-MIPS SUN SPARC processor will be required to perform ground-based data processing in the available time. Although a 30-MIPS processor is not currently available, judging from the fast pace of developments in the microprocessor industry it is reasonable to expect that one will be available before delivery of the HLBS. Since the conceptual design was started in 1988, SUN processors have gone from a maximum of 4 MIPS to the current maximum of 22.5 MIPS. The waveform algorithm processing time benchmarks were developed on a SUN-4/110 workstation. All the required software can be developed on any SUN-4 workstation, and will be loaded and tested on the actual system before delivery.

SUN-4 computers use the SUN Operating System, which combines AT&T's System V UNIX with Berkeley's 4.3/4.2BSD UNIX. UNIX is rapidly becoming an industry standard. It provides access to a wide range of third-party software products offering cost-effective alternatives to custom software development. A 'C' language compiler is included with the SUN operating system.

The Data Processing System will be provided with two gigabytes of disk space. The operating system, analysis software, third party graphics and database software, as well as the daily and cumulative survey databases, will be stored on this disk. An EXABYTE tape drive will enable the system to read the data gathered by the airborne computer. The drive will also provide backup capability for the data processing system. A conventional cartridge tape drive will be included to read SUN software distribution tapes.

The SUN workstation will be equipped with a 19-inch high-resolution monitor, a keyboard and a mouse. The workstation includes serial data ports which may be configured to provide connections for a number of different hardware devices, modems, printers or terminals. A compatible plotter for the output of the greyscale and sounding plots will complete the Data Processing System hardware. An overview of the SUN ground-based processing system is presented in Figure 5-20.

5.4.8 Database Requirements

Each survey flight will produce a new set of recorded data from the airborne system. Once this data is transferred from the tapes and processed, it will be loaded into a set of files for editing. When editing is complete, the data remaining will be combined with data from all other flights to produce the final survey results.

The datafile format must provide quick access to data in the format required for applying the processing algorithms to determine depths; it must also allow for the many types of searches required during editing. It will be possible to gather as much as one gigabyte of data in the air for one day. Minimizing disk space is therefore a prime consideration, and redundancy and key sizes must be kept to a minimum.

The relational database will be used for the HLBS. It will allow quick access to data organized into smaller files with common search criteria, such as XY position or confidence level, as keys. It will also allow searches on partial keys if a more general search is required. There will be some redundant data with the relational approach, because search fields are repeated in multiple fields. However, only existing data will be stored and no space

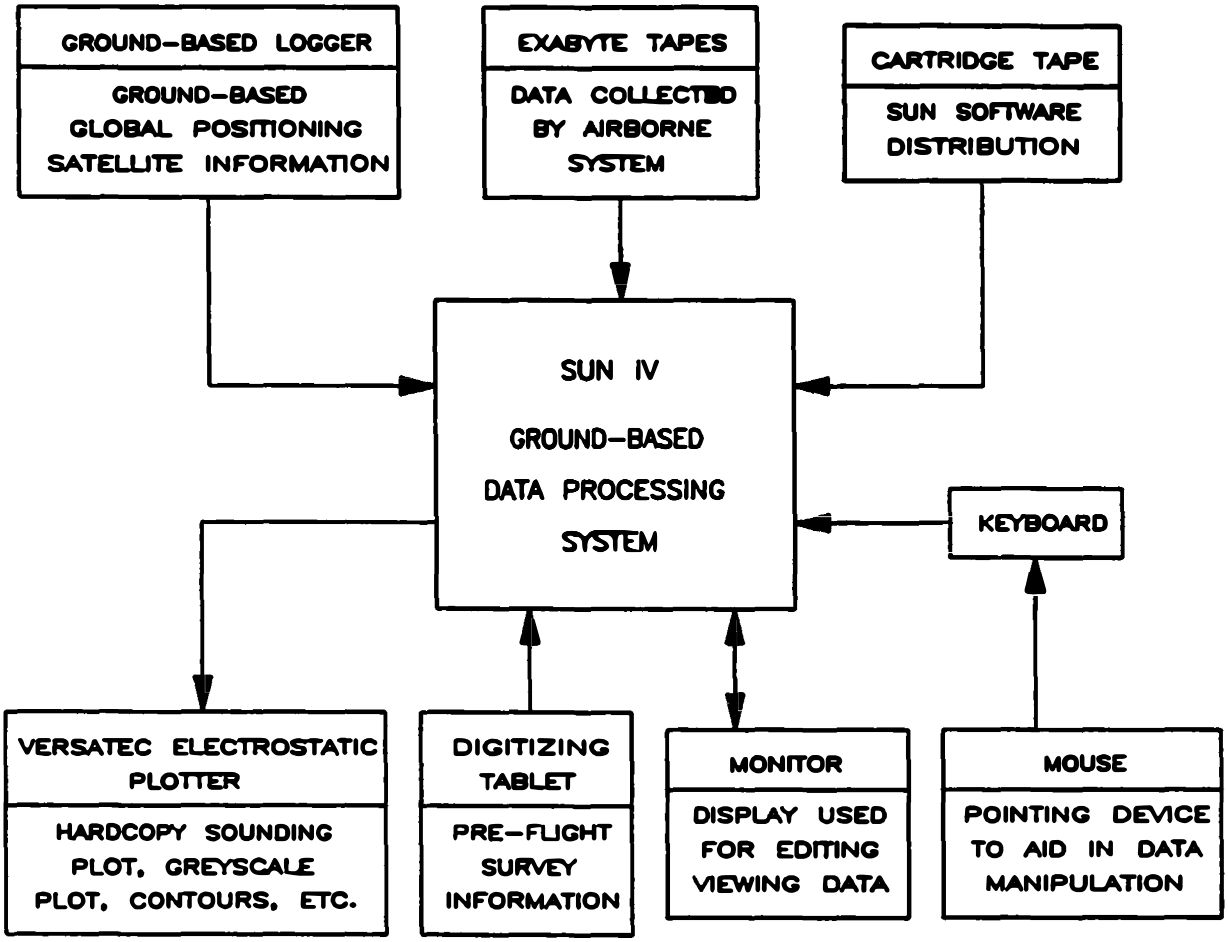


Figure 5-20. System input/output

will be wasted by missing data. Searches can be pre-defined for the usual requirements, such as flightline and confidence level, all data for an XY position, or tide corrections for a given sounding. New searches can easily be added during a survey, without programming, by using the end user query system. This makes the relational database a convenient model for programmers, providing the greatest flexibility of database definition and allowing keys and data elements to be added. The database definition of related files will also reduce any programming necessary when looking simultaneously at data from multiple files.

A relational database will meet the requirements identified for efficient use of disk space, quick access to data, increased programmer productivity, the flexibility to change the database definition as more surveys are run, and increased productivity during the editing process through easy end user data searches. There will be additional processing and system memory overhead when multiple files are linked to perform searches. This link is done at run-time to preserve maximum flexibility. Memory and processing power will be available during the editing process because these same features will be required by the algorithms used during Phase II processing for depths. The amount of redundant data, necessary to provide the link key fields, will be minimized through database design and programming effort.

SECTION 6.0

HELICOPTER IDENTIFICATION AND MOUNTING PLAN

6.1 Helicopter Selection

Various helicopter types have been considered for the installation of the laser baythymetry system. They have been evaluated on the basis of commercial availability and on the special requirements of the HLBS system: weight, hardware dimensions, and power.

The evaluated helicopter types are listed in Table 6-1.

Table 6-1
Helicopter Types Evaluated
For HLBS System

Manufacturer	Model Number
Bell	204B, 205A-1, 212, 412
Aerospatiale	SA360, SA365
Westland 30	100-60
Sikorsky	S55, S58, S70, S76

The critical design parameters of the HLBS that will have an effect on the selection of the helicopter are listed in Table 6-2.

Table 6-2
HLBS Physical Requirements

Power:	Total: 4 kW DC: +28V, 20 to 50% of power AC: +115V, 400 Hz, 50-80% of power
Payload:	Sensor: 350 lb. Equipment: 400 lb.
Volume:	Sensor: 42" x 42" x 21" Equipment: Two 19" racks, 42" minimum height

A variety of helicopters can provide cabin space and payload capability. Of particular concern is the available electrical power supply. The Bell 205A-1 and 212, as well as the Sikorsky S76, are the most promising based on the requirements.

The Bell 412, which is similar to the Bell 212, will also meet the requirements of the HLBS system, but it is not as readily available commercially as the Bell 212. The Bell 205A-1 provides 300 A current at +28 VDC, and 250 VA at 400 Hz. Additional AC power can be provided with the use of an external inverter. The cargo area is 7'8"L x 8'W x 4'4"H. The cabin floor and aft bulkhead are equipped with fittings that can serve as attachment points for the HLBS equipment.

The Bell 212 provides 400 A current at +28 VDC, and 750 VA at 400 Hz. The cargo space is similar to that of the Bell 205A-1. The dimensions are 7'8"L x 8'W x 4'1"H. The payload capacity is also similar to that of the 205A-1, at about 5000 pounds.

The Sikorsky S-76 provides 400 A current at +28 VDC, and 7.5 kVA AC current at 115 V. Its payload capacity is 4500 lb.

All three helicopters, as well as the Bell 412, are suitable for installation of the HLBS. The Sikorsky S76 is the most suitable aircraft for meeting system requirements. However, when operating costs and availability are considered, the Bell 212 is selected as the helicopter of choice. According to the American Civil Aircraft Registry, one hundred and thirty-five Bell 212 helicopters are registered in the United States.

6.2 Sensor Mounting

A preliminary equipment mounting arrangement has been prepared for this aircraft. Several possible arrangements for mounting the sensor.in the Bell 212 have been investigated:

1. Internal mounting, with a viewport in the helicopter fuselage

2. External mounting on the belly of the aircraft

3. Internal mounting, scanning down from the cargo doorway

The prime mounting requirements are that the system be easily and quickly mounted on, and removed from, the aircraft. This necessarily dictates a configuration that requires minimal modifications on the helicopter. Since it is desirable that the system be easily moved from one aircraft to another, the option requiring a viewport is not preferred. Moreover, such an installation would represent a major modification. The Bell 205A-1 and 212, and the Sikorsky S76, all have fuel tanks in the area under the cabin floor, complicating viewport design. External mounting under the helicopter is feasible, but comfortable clearance margins cannot be found underneath the aircraft.

Internal mounting, with the sensor viewing down from the doorway, is the most attractive mounting arrangement. In this configuration, the sensor's scanning mirror is designed to extend outward from the cabin, as shown in Figure 6-1.

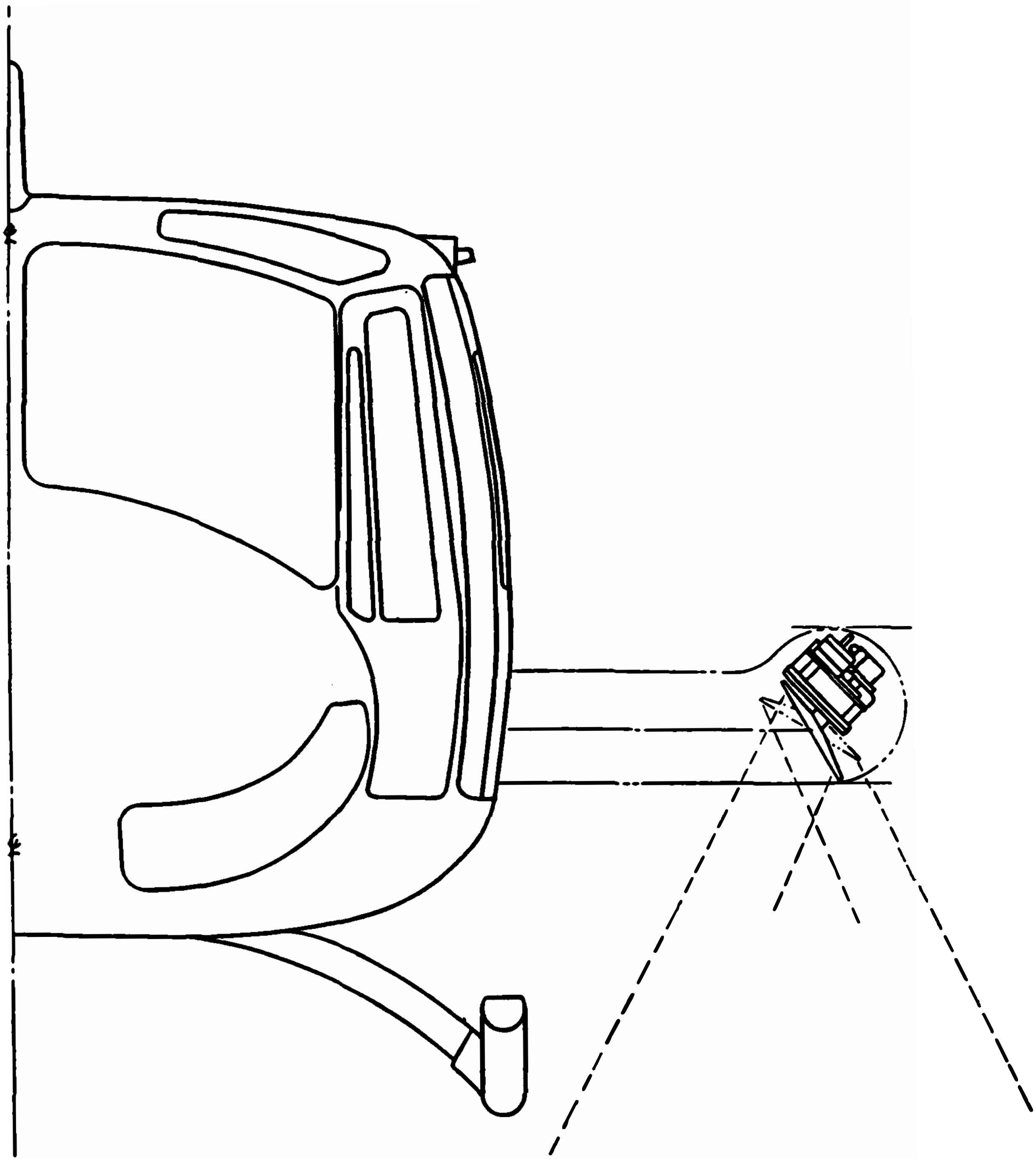


Figure 6-1. Side-mounted sensor

With such a mounting arrangement, moving the system from helicopter to helicopter will be relatively simple as there will be easy access to the sensor for installation and removal, and no modifications will be required.

The general arrangement of the equipment within the helicopter is presented in Figure 6-2.

The equipment electronics units and the sensor will have a combined weight of less than 750 pounds. The sensor will be mounted in a pod extending four feet outward, horizontally, from the left side of the helicopter. The tube of the pod will rigidly connect to the sensor box inside the aircraft. The pod cone will house the scanning system and video camera; the sensor box will contain the laser head, receiver optics, detectors and receiver electronics. Such a division is primarily driven by the desire to keep the weight outside the helicopter to a minimum. A universal interface panel will be designed to fit into, and replace, the left cargo side-door housing of the helicopter.

The HLBS signal processing and display equipment will be mounted in two standard 19-inch racks, or equipment stations. Each equipment rack will be about 42 inches in height. The preliminary plan for equipment distribution in the racks is for the station farthest from the sensor to house the acquisition control and display subsystem, and for the other station to house the aircraft positioning subsystem and the laser electronics. Equipment and racks will be designed to meet the landing and crash impact survivability standards required for certification by the United States Federal Aviation Administration (FAA) and the Canadian Department of Transport.

The preliminary equipment layout for the Bell 212 is shown in Figures 6-3 through 6-5. Figure 6-3 presents a plan view of the proposed installation. It shows the two operators seated in front of the two electronics consoles, and the sensor viewing out through the helicopter cargo bay door. Figure 6-4 is a side view of the equipment installation. A preliminary layout of the electronics consoles is presented in Figure 6-5.

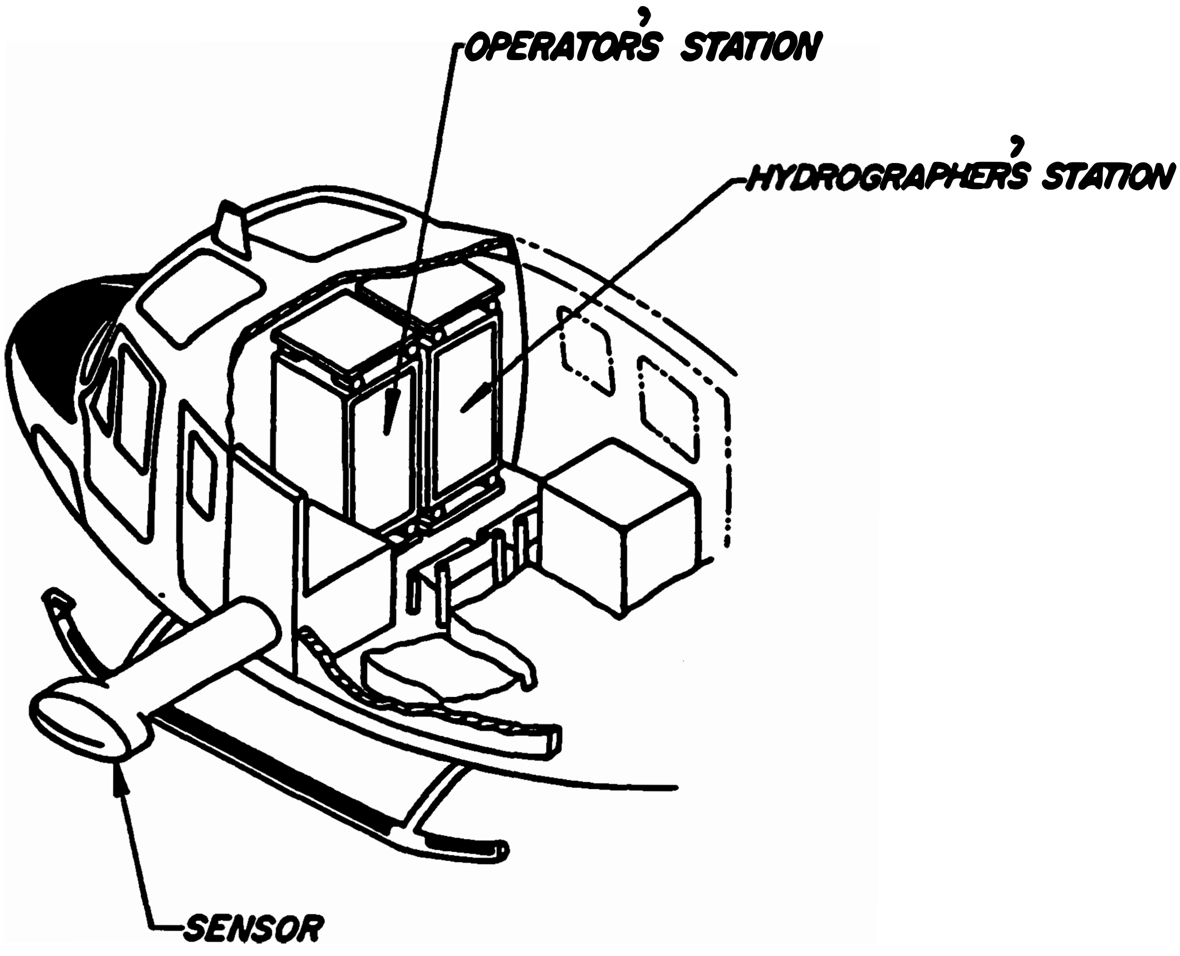


Figure 6-2. Arrangement of equipment

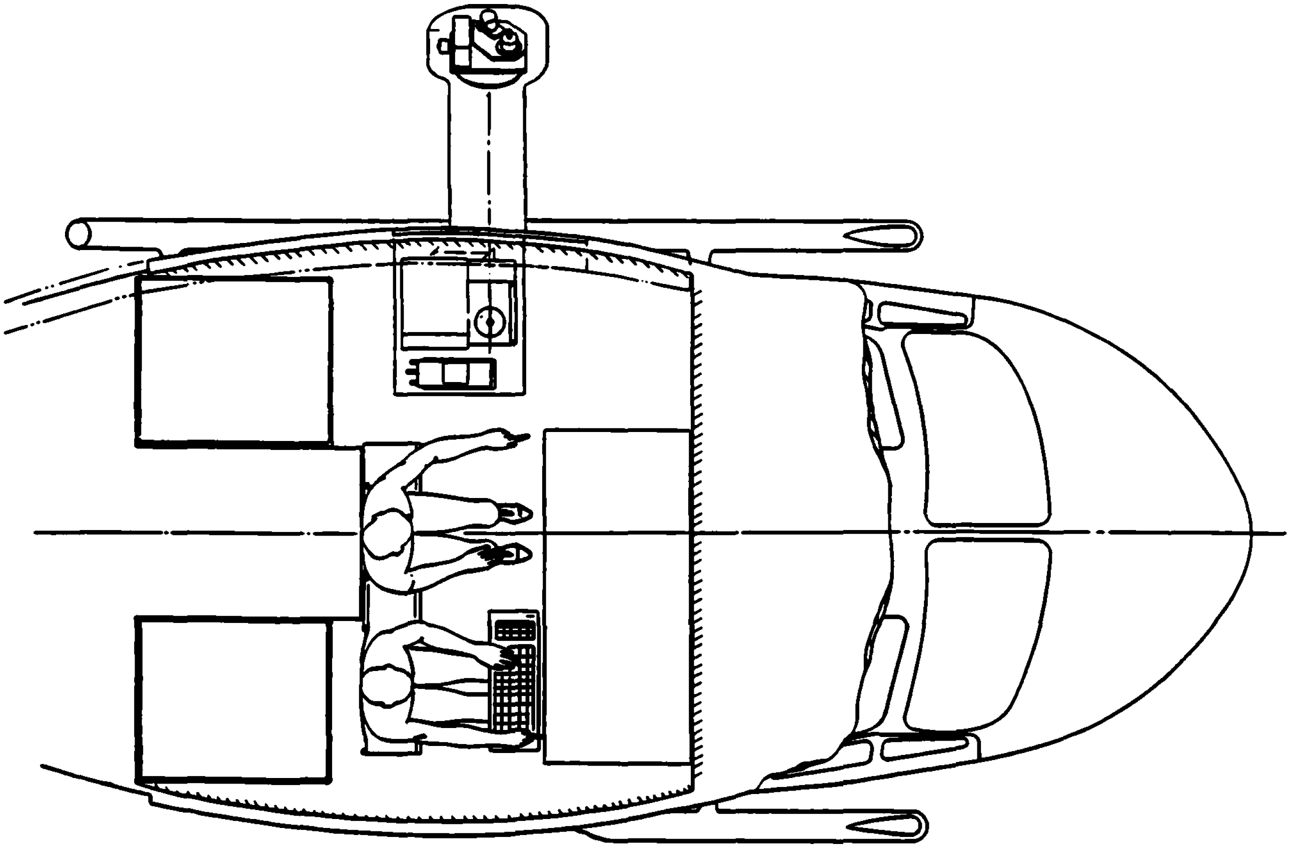


Figure 6-3. Top view of equipment

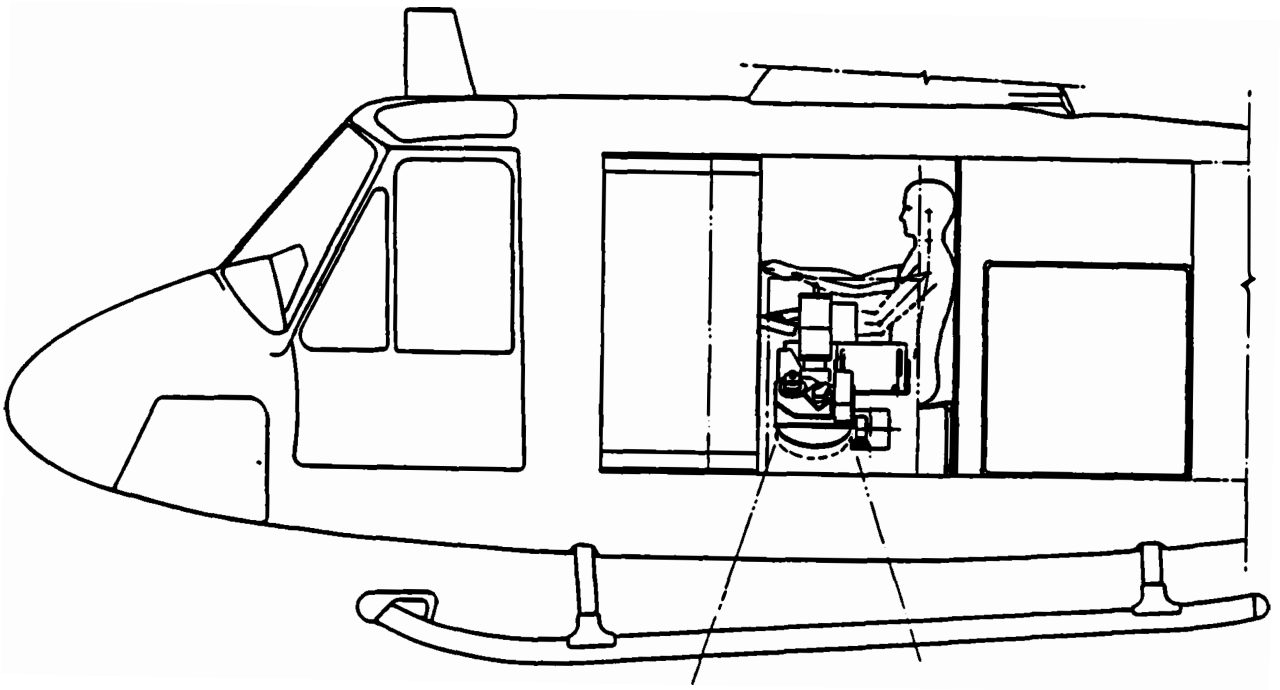


Figure 6-4. Side view of equipment

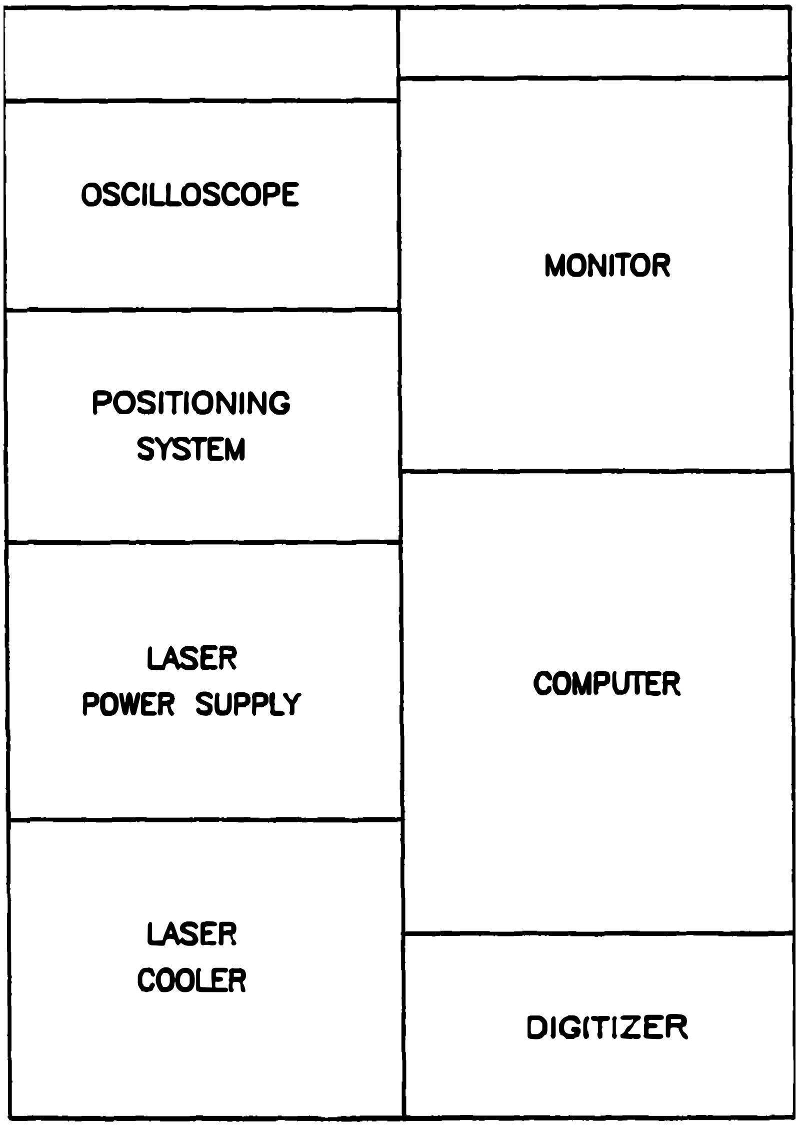


Figure 6-5. Preliminary layout of electronics consoles

SECTION 7.0

COMPATIBILITY WITH FAA

A careful analysis and comparison of the necessary air approval and certification procedures in both Canada and the United States has been undertaken. The results of this investigation indicate that the best way in which to proceed with airworthiness approvals for the HLBS system will be to file first for Canadian Department of Transport (DOT) approvals for the helicopter in which the prototype bathymeter system is to be installed, and then to apply for a Supplementary Type Approval.

Once this has been done, the approval can be transferred to the United States Federal Aviation Administration (FAA) for review and approval for a helicopter of United States registry. This approach is recommended for a number of reasons. Since the prototype system will be designed, fabricated and assembled in Canada, the advantage of dealing with local regulatory authorities is obvious. In addition, it has been determined that approval of the initial design submissions can be obtained much more quickly through the DOT than through the FAA.

In Canada, DOT must grant approval before any modified or repaired aircraft can be returned to service. Their approval is divided into the two stages of design approval and conformity inspection. The design of a modification can be approved either by DOT Engineers or an authorized Design Approval Representative Engineer (DAR). After an aircraft modification has been completed, it will be inspected for conformity with the approved design by a DOT CERTIFIED, B-Licensed Aircraft Maintenance Engineer (B-AME).

7.1 Required DOT Documentation

The preparation of several special-purpose documents are associated with the approval process. The DAR- or DOT-approval documentation consists of drawings of the modifications, engineering substantiation of airworthiness, a Requirements Compliance Program (RCP) and DOT Form AE-100.

The Requirement Compliance Program is a reference document describing how each airworthiness requirement is being addressed. Typically, the RCP is a form that references the modification drawings, the engineering report, and applicable flight test reports. It must be supplemented by a thorough Requirement Compliance Section (RCS) in the engineering report addressing each requirement. DOT Form AE-100 is used by the DAR or DOT Engineer to certify that the design meets the requirements for approval. After conformity inspection, the B-licenced AME will produce a copy of DOT Form AI-101, which certifies that the modification has been inspected and found to conform with the approved drawings.

7.2 Flight Testing

For any installation which may have a major impact on the performance of the aircraft, a flight test will be required. The flight test report will form a part of the approval documentation. The flight test can be performed by a DAR Test Pilot or by any experienced pilot with a sufficient number of flying hours on the aircraft being evaluated. The flight test report can be approved only by the DAR Test Pilot that performed the flight test or by a DOT Engineer.

If any changes in aircraft performance characteristics occur they must be noted and a Flight Manual Supplement prepared. This document must detail the changes that a pilot has to expect when flying the aircraft. The Flight Manual Supplement must be attached to the aircraft's approved Flight Manual. The supplement can only be approved by a DOT Engineer of sufficient rank, based on a recommendation for approval from a DAR Engineer or DAR Test Pilot.

7.3 Supplementary Type Approval

Application may also be made for a Supplementary Type Approval (STA) for the modification. This approval would be based on the supporting documentation already described, and would be design approved for any aircraft of the same type. Similarly, application for an American Supplemental Type Certificate (STC) may be undertaken. An STA/STC approval will be required to permit the HLBS to be removed from and reinstalled in aircraft of the same type.

As the HLBS will be installed on civilian aircraft in the United States, the American airworthiness approvals must also be obtained. Canada has adopted the Federal Aviation Regulations (FAR) of the United States. Thus the same basic criteria must be met for both Canadian and American approvals. Moreover, Canada and the United States have a bi-lateral agreement that will permit Canadian approved modifications to be used. However, there are certain restrictions which apply.

The FAA of the United States will not recognize Canadian DAR approvals. This means that a Canadian DAR cannot approve modifications to American aircraft. Moreover, a Canadian-based company cannot request an American STC without first obtaining a Canadian STA. As Optech is likely to hold the STA/STC, the approvals will have to be done through the DOT.

The issue of flight testing is also critical. If a US institution is to provide the aircraft that will be used for the approval flight tests, it will likely mean that testing will be done through DOT; this could pose problems. While the FAA has indicated that it would be willing to allow Transport Canada to issue a flight test permit for tests in the United States, DOT will be responsible for providing inspection and monitoring functions in the United States.

DOT has not yet indicated whether it is willing to do this. If the USACE holds the STA/STC, this issue will not arise unless flight testing is required in Canada.

Flight testing can be divided into two categories: flight testing to check the system performance and flight testing to obtain airworthiness approvals. It is possible to obtain an experimental flight test permit allowing a certain amount of test flying for experimental purposes, before having to perform a full aircraft performance flight test. This enables a certain amount of flying without the need for modifications to be made before the final airworthiness approvals are required.

7.4 HLBS Compliance with DOT and FAA

The HLBS system will use a number of off-the-shelf, available components, subsystems and circuit boards. All externally-procured assemblies will be assessed for suitability of operation in the intended environment and will be ruggedized where necessary to ensure reliable operation. For the custom designed circuits, high quality commercial-grade components will be used. Printed circuit boards, laid out to industrial standards, will be used in all electronic subsystems, and standard wiring and assembly procedures will be applied.

To ensure successful operation in a helicopter environment, an extensive testing program will be conducted with the HLBS. This will include thermal, shock and vibration testing as well as electrical testing to assess the extent of possible electrical interference. Tests will be done by an independent testing lab in accordance with the procedures outlined in "Environmental Conditions and Test Procedures for Airborne Equipment" (Document No: RTCA/DO160B - July 1984), as applicable to the HLBS system. Test results will be submitted to FAA if required.

SECTION 8.0

SYSTEM PERFORMANCE SPECIFICATIONS AND OPERATIONAL LIMITATIONS

The HLBS expected performance capability is summarized in the system specifications given in Table 8-1. As with any other tool, next to the limitations set by the parameters of its design and construction, the main limitations to its usefulness arise from the external environment. Viewed from the broad perspective, the main areas of limitations are maximum and minimum depth, weather and bottom structure (composition).

8.1 Maximum and Minimum Depth

With the system depth performance capability of $3 \leq kd \leq 5$, penetration of up to 50 m will be possible in very clear water. Penetration in murky harbour or bay waters may be less than 10 m depending on the actual value of k. In moderately clear waters typical maximum depths will be in the 20 m to 30 m range. Operationally, an approximate idea of the depth and water clarity will be required prior to the survey mission. Knowledge of water clarity in terms of secchi depths will be adequate.

As water clarity is very frequently a dynamic parameter, changing with the environmental (wind, run-off etc.) and biological (algae blooms etc.) activity, windows of opportunity, when water clarity is at optimum, must be exploited to maximize the usefulness of the system in areas where water-clarity/depth-combination may be near the limit of the system capability.

Depth measurement capability is also limited on the shallow side, in this case by the system hardware parameters. This minimum depth will be in the range of 1 to 1.5 meters.

8.2 Weather

Several weather parameters act to limit the system performance in different ways.

8.2.1 Wind/Waves

Winds in excess of approximately 20 knots generate whitecaps and foam on the surface which prevent the laser beam from penetrating the surface efficiently, and hence limit the system effectiveness. In addition, greater wave amplitudes generated by the conditions of high wind speeds introduce loss of precision in the wave-correction procedures as well as larger beam-steering errors at the air-water interface. These effects degrade depth and horizontal accuracy respectively, and are a general limitation on system usefulness. An additional effect of high wind/wave conditions is that in soft-bottom areas poor water clarity may result from resuspension of bottom sediment. However, wind conditions that generate whitecaps over a significant fraction of the surface and stir up the bottom sediment are generally severe enough to discourage flying for safety reasons. As such, they do not impose, in this context, a limitation substantially different from that of boat operations.

8.2.2 Fog and Precipitation

Heavy fog, and rain or snow, degrade the system operation in a two-fold manner. Greater signal strength losses in the atmosphere under such conditions result in some depth penetration degradation, and the creation of strong atmospheric backscattering signatures may, at times, degrade the reliability of underwater-data acquisition. Again, however, safety considerations would in most such cases likely preclude the flying itself.

8.2.3 Ambient Light Conditions

At low latitudes, during several hours around noon, sun-glint conditions on clear days will limit the system depth performance capability. Since the system views the water at approximately 15° to 20° angle from nadir, sun reflections coincident with this look angle will generate additional noise. Operationally, therefore, flying around noon in those regions should be avoided on clear days only. At higher latitudes, such a limitation would not exist. At all latitudes, however, improved depth penetration is obtained for conditions of increasing darkness.

8.3 Bottom Structure

Operation in areas where bottom is heavily vegetated or covered with "fluid mud" will present serious challenges to the system. Performance of a lidar bathymeter system off such bottoms is not yet known and remains to be investigated during the field-trials evaluation phase. A similar evaluation of experimental performance data will be required for bottoms with very steep slopes before meaningful conclusions can be made for such conditions. These areas of ambiguity present similar challenges to the much older acoustic technique.

8.4 Other Limitations

8.4.1 Surf Zone

To the extent that the surf zone contains both highly asymmetric wave structures and large amounts of foam, and given the system minimum depth capability of 1 to 1.5 m, the system usefulness for sounding in the surf zone is still very doubtful. This transition zone is likely the most difficult area to deal with and, as such, is best left to be dealt with at a later time.

8.4.2 Accuracy

The expected depth accuracy of 0.3 m will limit the usefulness of the system to those applications which do not require any greater accuracy in depth measurements, such as reconnaissance surveys, condition surveys, beach and bank monitoring surveys, underwater obstruction surveys and general, large-area hydrographic surveys.

The positioning accuracy of the system is limited mainly by the accuracy in determining the position of the aircraft. Using microwave range positioning or GPS, the limit to aircraft positioning accuracy is approximately 2 meters, with, typically, expected accuracies in the 2 to 5 meter range. Good prospects exist, however, that in the near future the aircraft positioning accuracy, in an operational mode, of less than 0.5 m will be possible through the phase processing of the GPS signals.

8.5 Overall Performance Capabilities

Overall the performance capabilities of the HLBS described here will greatly extend the abilities of the USACE to undertake a broad range of survey applications more effectively. Even with the limitations described above, the HLBS represents a quantum leap forward in bathymetry technology compared to existing methods. This new technology, however, will not replace the present acoustic systems; rather, the two will be complementary. By utilizing each type of technology in its optimal situations, the overall capabilities of the USACE to fulfill its mandate will be greatly enhanced.

Table 8-1

HLBS System Specification

System

Water Depth Penetration:	kd = 4, daytime (1) kd = 5, nighttime
Depth Accuracy:	30 cm, (one sigma)
Horizontal Accuracy:	4 m, (one sigma)
Operating Altitude:	100 to 1000 m, 200 m typical
Ground Speed:	0 to 100 m/s (2)
Swath Width:	1/2 operating altitude (3)
Area Coverage Rate:	3 to 80 km^2/hr (4)
Operational Capability:	Day or night
Eye Safe:	Eyesafe from operating altitude

Laser

Operating Wavelength:	532 and 1064 nm
Pulse Repetition Rate:	200 Hz

Receiver

Aperture:	20 cm
Telescope type:	Reflective, Cassegrain

Scanner

Type:	Quasi conical
Sweep Angle:	±15 degrees
Rotation Rate:	0 to 20 Hz

Aircraft Positioning System

Type:	Microwave transponder or Global Positioning System

Attitude Measurement System

Accuracy:	Roll:	0.05°
	Pitch:	0.05°
	Heading:	0.4°

Data Acquisition and Control System

Processors:	680XX/VME Bus
Data Storage:	8 mm Helical Scan Tape

(Continued)

Table 8-1 (Concluded)

Airborne Displays/Monitors	
Operator:	1 real-time depth display/status monitor
Pilot Guidance:	1 flight-line management display
Data Processing Facility	
Capability:	2 hrs of airborne data processed overnight
Processor:	SUN-4
Data Storage:	2 Gigabytes disk space
Data Hard Copy:	1 colour plotter
Monitors:	1 colour graphics workstation
System Size/Weight/Power	
Airborne:	
Size:	42" x 42" x 21" lidar transceiver 2 x 42"-high 19" rack
Weight:	350 kg
Power:	4 kW (+28 VDC/110 VAC, 400 Hz)
Ground-Based:	
Size:	42"-high 19" rack 21" CRT and keyboard
Weight:	80 kg
Aircraft Types:	Bell 212, 205A-1, 412 Sikorsky S-76 Fixed-wing aircraft

Notes: (1) k is the water diffuse attenuation coefficient
for $k = 0.1\ m^{-1}$, $d = 40$ m max. in daylight
for $k = 0.5\ m^{-1}$, $d = 8$ m max. in daylight

(2) Some forward velocity is necessary to achieve area coverage

(3) Depends on scanner firing angles

(4) Depends on desired sampling density

Specifications are nominal.

APPENDICES

INTRODUCTION

These Appendices contain the following plans, as defined in the HLBS Phase I statement of work: training plan, system documentation plan, diagnostics test plan, system laboratory test plan, field test plan, and initial flight test plan.

The structure of the report is as follows: Appendix 1 presents the plan for training USACE personnel in order to provide a full working knowledge of system installation, operation and data processing. Appendix 2 discusses various aspects of system documentation, including Optech's current procedures and the documentation plan for Phase II of the HLBS program. Appendix 3 outlines the proposed diagnostics test plan. Appendix 4 describes the plan for testing the system in the laboratory. The field test plan is presented in Appendix 5, which outlines the plan for testing the functionality of the system after it is shipped from Optech to the point where it is ready for field performance evaluation. Appendix 6 gives a detailed discussion of the plan for demonstrating that the HLBS meets performance specifications, and determining the performance envelope of the system.

APPENDIX 1 TRAINING PLAN

1.1 Classroom-Course Structure (Theory, Operation, Maintenance)

The Airborne and Ground-Based Systems of the HLBS are covered in different parts of the training program as outlined below. The HLBS system training will be provided through classroom sessions covering the Principle of Operation, System Specifications and Limitations, and System Applicability. The training on the Airborne System will include a small segment on theory and explanation of the algorithms chosen. A combination of classroom and in-helicopter training will be used to cover the operation of the Airborne system as well as safety-related issues and operator precautions. The Maintenance segment will include installation, troubleshooting and scheduled maintenance. The segment will include classroom and in-helicopter training. Training on the Ground-based system will begin with theory including a description of the algorithms used. The operation of the system will be covered through a combination of classroom sessions and hands-on experience with the applications. Maintenance on the ground-based system will be covered in a classroom session.

1.2 HLBS Training

1.2.1 HLBS Introduction - 1 Day

The purpose of this classroom session is to provide an introduction to Bathymetry and specifically the HLBS. This session will be of interest to all who are involved in determining the suitability of this survey method, or who will be working with the HLBS or analyzing the lidar data.

<u>Topics</u>

Bathymetry - A history of this technology

Optech - Optech experience in this field

HLBS - The origin of this project
Intended applications
Principle of operation
Significant design decisions
Overview of the system
Airborne components
Ground-based components
System outputs

1.2.2 HLBS Specifications and Limitations - 1 Day

This classroom session covers all the specifications and limitations of the HLBS System including operational parameters, safety precautions and compliance with Federal Aviation Administration Regulations. This session would be of interest to those planning a survey with the HLBS or analyzing the results of a survey.

1.2.3 HLBS System Applicability - 1/2 Day

This classroom session covers all the known operational constraints for the HLBS and provides a list of considerations to be used in determining the suitability of the HLBS for a particular survey site. This session would be of interest to those planning a survey with the HLBS or analyzing the results of a survey.

1.2.4 HLBS Survey Operation - 1/2 Day

This classroom session outlines the functions performed in a complete HLBS survey, and discusses System Applicability, Operator and Hardware requirements, HLBS installation and diagnostics, Airborne Operation and Ground-Based Analysis. This course would be of interest to those planning a survey with the HLBS.

1.2.5 Airborne System Introduction - 1 1/2 Days

The Airborne System was designed to require minimal operator intervention. This classroom session describes the operation of the Airborne System and the operator interface. This session is of interest to all of the airborne crew for the HLBS system and for those analyzing the output lidar data.

Topics

Transceiver -	A discussion of the transceiver components: transmitter, scanner, primary and secondary optical systems, detectors and receiver electronics. A discussion of the function of Time Interval Counter and Waveform Digitizer.
Safety -	Eye protection and high voltages
Acquisition of data -	A description of all the hardware components in the Airborne system, what part they play and how this information is recorded.
Operator Displays -	An introduction to the operator displays and messages. General operation flow.

Pilot Guidance -	An introduction to the Pilot Guidance System, purpose, screens and messages.
Data Analysis -	An explanation of the algorithms used to calculate the data displays and control the system sensors.
Manual Control -	The manual control system, purpose and operation.
Aircraft Positioning -	The operation of the different aircraft positioning systems used.
Inertial Reference -	An overview of the inertial reference system used.
Video Camera -	Operation of the video camera and the reasons it is used.

1.2.6 Airborne System Operation - 2 Days

This lab session in the Helicopter includes the preliminary diagnostics, pre-survey operation, simulated survey operation including pilot guidance, a 1 hour flight for airborne operators, and shutdown procedures. Data gathered on video and data tapes during the field trials will be used to simulate actual flights for training in appropriate operator response. The full HLBS Airborne equipment will be installed in the helicopter to provide training on all the components and controls using the actual equipment. This session would be useful for all airborne scientific crew of the HLBS.

1.2.7 HLBS Installation - 2 Days

This lab session in the Helicopter describes and provides experience unpacking, installing, and testing and calibrating the HLBS in the Helicopter and removing and repacking the HLBS. This session is of interest to the installation crew for the HLBS.

1.2.8 Airborne System Trouble Shooting and Maintenance - 3 Days

This session has 2 classroom days and a one-day lab session in the helicopter. It focuses on the pre-flight trouble shooting procedures, in-flight troubleshooting and regular field maintenance requirements such as laser flashlamp changes. Maintenance Personnel will be given "hands-on" instruction. This session is of interest to those responsible for maintaining the HLBS.

1.2.9 Ground-Based System Introduction and Operation - 1 1/2 Days

This session provides an introduction to all of the Ground-based System processes. It would be of interest to those who will be editing or analyzing the output lidar data.

Topics

Phase I Processing -	The automated processing that occurs as the data is retrieved from the Airborne Tapes,and the available operator selections.
Phase II Processing -	The automated editing that occurs on the data now located in the Daily Database. The Operator decisions that affected this processing and the automatic and optional outputs from this processing.
Phase III Processing -	The Operator-controlled editing of the data in the Daily Database. The usual, mandatory or optional steps in this process. The optional outputs from this process. The option to update the final Survey Database.
Phase III Lab -	Hands-on experience with the Phase III menus, options, entry, reports and plots.
Pilot Guidance -	Training on preparation of survey area for pilot guidance system.
Ground-Based Lab -	Session to cover all of Ground-Based Processing from loading airborne data through editing.
Backup Procedures -	Backup Procedures.
Maintenance -	Maintenance Contracts, Hardware Maintenance requirements, Software Maintenance Requirements.

1.3 Number of Trainees

The minimum number of attendees would include two competent electronic-surveying technicians for airborne operation and two ground-based technicians for data processing. To provide a backup and more alternative scheduling options there should be at least two sets of Airborne and Ground-based operators. Optech would send support personnel to ensure a transfer of information and increase the support base beyond those involved in the field trials. At this point there may also be interested Survey contractors that would send teams. Some of the training courses are also appropriate for USACE Management involved in Organizing and Budgeting for specific surveys. The number of probable participants has been listed for each course.

Training Course	Participants
HLBS Introduction	
USACE ground-based technicians	4
USACE airborne technicians	4
USACE Survey Management	4
Optech Support	2
Possible Survey Company participants	4
HLBS Specifications and Limitations	
USACE ground-based technicians	4
USACE airborne technicians	4
USACE Survey Management	4
Optech Support	2
Possible Survey Company participants	4
HLBS System Applicability	
USACE ground-based technicians	4
USACE airborne technicians	4
USACE Survey Management	4
Optech Support	2
Possible Survey Company participants	4
HLBS Survey Operation	
USACE ground-based technicians	4
USACE airborne technicians	4
USACE Survey Management	4
Optech Support	2
Possible Survey Company participants	4

Training Course	Participants
Airborne System Introduction	
USACE ground-based technicians	4
USACE airborne technicians	4
USACE Survey Management	4
Optech Support	2
Possible Survey Company participants	4
Airborne System Operation	
USACE airborne technicians	4
Optech Support	2
Possible Survey Company participants	4
Pilots are required for two flights 1 hr each	
HLBS Installation	
USACE Installation technicians	4
Airborne System Trouble Shooting and Maintenance	
USACE airborne technicians	4
USACE Installation technicians	4
Optech Support	2
Possible Survey Company participants	4
Ground-Based System Introduction and Operation	
USACE ground-based technicians	4
Optech Support	2
Possible Survey Company participants	4

1.4 Available Space and Equipment

For the training sessions proposed 8 days of classroom time would be required with an additional 3 days of preparation time. There would be a maximum of 18 attendees per session requiring some table space. There should be an overhead projector and a chalk or white board available. Some access to administrative facilities would be desirable, for a quick photocopy or telephone call. For the 1 1/2 day session on the Ground-based system a smaller version of the Computer System would be required for training purposes. Small subsets of the field test data would be used in the training. This system would require two electrical outlets but otherwise has no special requirements. This session would have a maximum of 10 attendees so no special projection equipment would be required.

Since the equipment for the classroom sessions is very straight-forward and sessions would be scheduled well ahead of time, we have assumed that a meeting room at Optech would be available. If this is not possible any hotel meeting room could be used.

A total of 5 days of lab sessions in the helicopter are required to accomplish the proposed training sessions, as long as the number of attendees is minimized. The lab setup would be required 2 days before and one day after the training sessions for installation and removal. The lab sessions will take place inside the helicopter, so physical space is limited. The training on the airborne operation may require two long days with half the attendees arriving and leaving early if the number of participants is greater than can be accommodated in the helicopter.

The Airborne lab sessions will require all of the airborne HLBS equipment. This equipment will be installed and removed several times during the training sessions, so the spares will also have to be accessible. Most of the training will use a subset of the video and data tapes gathered during the field trials. These tapes will be used to simulate actual flights and allow training on appropriate operator response and the pilot guidance system. The installation and diagnostic sessions will use live operation of all the HLBS equipment. The Airborne Operation course will include two training flights of 1 hour each, held the same day. All other training will take place on the ground.

The Trouble Shooting and Maintenance course will require a clean work-area for changing the laser flashlamp.

1.5 Training Schedule

There will be a requirement of 60 days elapsed time to integrate information from the field test into the final documentation which will be available 30 days prior to training. Training can start 120 days after the completion of the field trials. Classroom training would begin the training schedule and the planned schedule is listed below.

HLBS Classroom Training Schedule

DAY 1	Preparation
DAY 2	HLBS Introduction
DAY 3	HLBS Specifications and Limitations
DAY 4	HLBS System Applicability & HLBS Survey Operation
DAY 5&6	Airborne System Introduction
DAY 7	Preparation
DAY 8&9	Ground-Based System Introduction and Operation
DAY 10&11	Airborne System Trouble-Shooting and Maintenance

HLBS Helicopter/Lab Training Schedule

DAY 1&2	Preparation
DAY 3&4	Airborne System Operation
DAY 5	Trouble-Shooting and Maintenance (This should take place right after Classroom DAYS 10&11)
DAY 6&7	HLBS Installation
DAY 8	Preparation day for removal of HLBS system.

APPENDIX 2 SYSTEM DOCUMENTATION PLAN

2.1 Overview of Optech Documentation Procedures

Optech has an integrated electronic/mechanical/optical documentation procedure. This procedure provides unified system design documentation linking the products of the electronics, mechanical, and optical departments. It provides for a common view into not only system documentation produced by Optech Inc. but also Optech Systems. It also provides logically produced by Optech Inc. but also Optech Systems. It also provides logically separate documentation on a subsystem level.

Documentation is controlled via a common project numbering scheme. This numbering scheme separates subsystem components from each other and enables the products of different departments to be recognized. The majority of the designs relate to various levels of assembly and detailed drawings. A natural entrance into the project is through these system drawings enabling one to logically descend the hierarchy of systems and subsystems. The format is as follows :

123 - 21 C 11
. drawing number (00-99)
.... Size code (A,B,C,D,E)
.... Assembly (Subsystem) Number
.... Project Number

By specifying a drawing number it is possible to find the electronic systems associated with that assembly. The exact component or function is found by following the electronic documentation.

The link between these system design documents/drawings and software documentation is the software detailed design document (SDD). Optech has adopted a tailored form of Mil-Std 2167A for use with in-house software development. While the documentation system in this standard is different from the other departments, the SDD provides a common bridge. The adaptation of 2167A was made due to the need to manage large software projects. The mechanical department calls this SDD a software master in order to maintain a compatibility with earlier projects. The earlier projects usually specified a software master which was a list of the firmware programs present in the system.

2.1.1 Mechanical/Optical Documentation

During the analysis, design, and implementation phases of the project, design documents/drawings are produced. These products of the mechanical/optical department are described in the following paragraphs.

2.1.1.1 Assembly Drawings

Assembly drawings provide global description at the system and subsystem level. They usually contain references to other assembly drawings and detailed drawings.

2.1.1.2 Detailed Drawings

Detailed drawings provide a detailed description of mechanical and optical components of the system or subsystem. They usually contain a backward reference to other drawings indicating location within a system or subsystem.

2.1.1.3 Drawing Lists

A drawing list is a set of allocated numbers for identification of the drawings comprising the project. These are used primarily as control documents to ensure consistency between different drawings and originators.

2.1.1.4 Project Drawing List Legend

Each project has a unique drawing list legend specifying all the assembly drawings encompassing the infrastructure of the system. Each entry in the legend points to the assembly drawing associated with it.

2.1.1.5 Manufacturing Methods and Procedures

Manufacturing procedures are documents instructing vendors on specific techniques Optech requires for manufacturing a particular item. These can be paint finishes, anodizing processes, welding procedures, etc.

2.1.1.6 Parts List

This list provides a description of all parts required for construction of one or more subsystems.

2.1.1.7 Software Master

As described earlier,the software master is a bridge to the software design documentation. Earlier projects used this as a list of those firmware programs present for the necessary functioning of the system.

2.1.2 Electronics Documentation

During the analysis, design, and implementation phases of the project, design documents/drawings are produced by the electronics department. The products of the electronics department are described in the following paragraphs. As indicated before, the electronics department uses document numbering similar to the mechanical department.

2.1.2.1 Schematics and Layouts

Circuit Schematics are produced as a result of the preliminary and detailed design phases. Printed circuit board layouts are constructed during the implementation phase of the project.

2.1.2.2 Interconnect Diagram

The interconnect diagram indicates the electrical connections between all hardware modules.

2.1.2.3 Cabling List

The cabling list provides a description of cable connections between physical subsystems and components.

2.1.2.4 Pinout Lists

The pinout lists give information on integrated circuit placement on PCB's.

2.1.3 Software Documentation

Software documentation follows from a tailored version of 2167A. Software Requirements Specifications (SRS), Software Detailed Design (SDD), Interface Reqs Specs (IRS), and Interface Detailed Design (IDD) documents are issued for each Computer Software Configuration Item (CSCI). The choices of CSCI's are formulated in the Software Requirements Analysis phase of the software development life-cycle. Other documents are issued as a result of the various reviews and audits. A software programmer's manual, software user's manual, and other various support documents are issued at the conclusion of the project. Besides these, configuration-controlled source code and executable code, along with version description documents and software product descriptions, are released.

2.1.4 Maintenance Manuals

Maintenance manuals are created to meet a variety of company and user requirements. The user is not normally expected to engage in complex repairs of any delivered system. A user maintenance manual describes first-line maintenance procedures. Another maintenance manual is provided for Optech technicians to allow them to find and correct the source of trouble quickly.

2.2 USACE Documentation Standards

2.2.1 Technical Report Format

Technical reports will follow the format of USACE Instruction Report ITL-86-1. This includes but is not restricted to technical reports produced to describe field tests, results, and performance capabilities. Optech reserves the right to follow its own internal technical report format should that format convey the necessary information more easily.

2.3 HLBS Hardware Documentation

The following hardware documents and manuals will be supplied with the system upon delivery. Certain documents cannot be supplied as they contain proprietary Optech information previously developed.

2.3.1 Interconnect Diagram

The interconnect diagram will be supplied to allow the system to be mounted or dismounted from the helicopter. This diagram will be accompanied by a short document describing the assembly procedure for the system.

2.3.2 Cabling Lists

Cabling lists will be supplied with the system upon delivery. These lists will aid the assembler in constructing the system. The various data paths will be identified and described.

2.3.3 Maintenance/Troubleshooting Manual

A maintenance and troubleshooting manual will be delivered with the system in order to allow the operator to perform first-line maintenance. This manual will cover troubleshooting procedures for various minor problems. It will also cover preventive maintenance methods in order to prevent the occurrence of serious problems.

2.4 Software Documentation

The documentation included with the software will be the source code, a software product description document, and a user maintenance manual to allow some limited end-user modification of the product.

2.4.1 Software Product and Version Description Document

The software product and version description document describe the software system and its various subsystems. In the event of a second or subsequent release of the HLBS software, a version description will also be released with it to itemize and explain the differences in the new release.

2.4.2 Software Maintenance Manual

A software maintenance manual will be included as part of the software documentation. This manual will enable the user to make limited changes to the man-machine (or user) interface. This interface consists of menus and windows displayed on the CRT.

2.4.3 Source Code

The source code will be included as part of the software documentation. This source code will be documented according to internal Optech code documentation standards.

2.5 System Documentation

The following sections describe general system documentation not falling under previous paragraph headers.

2.5.1 System Product Specification

A system product specification will be issued describing the HLBS product upon delivery. This specification shall provide an overall system description followed by a detailed description of each subsystem forming HLBS. This product specification shall describe modes of operation, ranges, tolerances and deficiencies on each of the following major subsystems.

a. LIDAR Transceiver Subsystem
b. Acquisition, Control and Display Subsystem
c. Aircraft Positioning Subsystem
d. Data Processing Subsystem (ground-based).

2.5.2 System Test Procedures

The system test procedures will describe all HLBS subsystems that will be tested. Each subsystem will have a detailed list of subsystem parameters and functional requirements to be tested. The overall system parameters and requirements will also be defined. This plan will define the system acceptance test procedure (ATP). The results of the application of this procedure during the system integration phase of this project will be added as an annex to the ATP.

2.5.3 System Diagnostics Test Procedures

The system diagnostics test procedures will describe the system diagnostics to be tested. It will define the field calibration parameters and both routine and preventive maintenance parameters.

2.5.4 System Field Test Procedures and Report

The detailed system field test plan will define field parameters to be tested. It will also define ground-truth parameters required, and evaluate potential test-sites. It will define horizontal control requirements, and evaluate techniques for decoupling z-accuracy measurement from x, y uncertainty effects. It will also identify field mobilization and demobilization requirements. Sites will be selected to provide proper trial coverage.

Upon completion of the field trials, a technical report will be issued to indicate the types of tests and their corresponding results. Data collected during the trials will be integrated and analyzed. This report will point out system strengths, capacities, limitations and inadequacies.

2.5.5 System User's Manuals

There will be two user's manuals covering HLBS operation and use. These will be an airborne system and a ground-based system manual. The airborne system user's manual will cover the needs of both the pilot and the mission specialist. The ground-based systems manual will cover the needs of a variety of different types of operators and users.

The airborne system manual will aid the hydrographer in preparing a flight plan to adequately cover the survey area.

The ground-based system manual will aid different classes of users in optimizing their use of the system. These users range from experienced hydrographers interested in preparing detailed charts to novel users and operators preparing data batch runs.

All user manuals will be written in an internal Optech format. Production of the user manuals will begin during the analysis phase so as to maximize their applicability and clarify the man-machine interface.

APPENDIX 3 HLBS DIAGNOSTICS TEST PLAN

The diagnostics test plan is an outline of procedures to ensure the accuracy of recorded data. General diagnostics should be carried out before every survey - these will probably be a subset of the flight test procedures. More detailed diagnostics will be necessary if there is an obvious subsystem failure or a strong suspicion of corrupted data acquisition. Some simple checking will be possible in the air but more extensive checks will only be possible on the ground. The most critical parameters are those which affect the accuracy of the XYZ coordinates of the soundings.

3.1 Airborne Diagnostics

The primary indication of problems will be the real-time colour depth display. A reasonable display means the system is functioning properly. An improper display will instantly alert the operator, who should be able to narrow down the problem to a major subsystem within a few moments. Visual observation and laser power monitor output will verify transmitter integrity. Scanner failure will also be apparent to the operator. The receiver detector will have auxiliary outputs for quick confirmation of signals. Environmental conditions could also cause peculiar returns and this can be instantly monitored by eyesight or by the video camera display. The inertial reference system can be checked for reasonable outputs by observing the displayed attitude angles. The computer will also be checking for complete and reasonable data as it records. It will prompt the operator when an error is detected.

Once the faulty subsystem is located, attempts to correct the problem can be initiated. If it is mission critical and insurmountable in the air, then the flight must be aborted.

3.2 Ground-based Diagnostics

There are many parameters which affect the accuracy of the soundings. The depth extraction depends upon the receiver detectors and electronics, the digitizer and the extraction algorithm. The raw depth also has to be corrected for the off-nadir angle, waveheight, and several biases, including water propagation bias (dependent on optical depth), surface marker calibration, and PMT and log amp delays. Most of these can be checked individually, and the results stored. For routine diagnostics, the processing chain can be tested by using an optical simulator which has known depth extraction. This will quickly verify the integrity of the receiver, digitizer and algorithm. The bias corrections mentioned above can be tested with the optical simulator by varying the simulated depth and amplitude of the returns. Correction for the off-nadir angle will require angle inputs which simulate the inertial reference system. Verification of the wave height correction algorithm will be more difficult. However, it is possible to use a digital waveform simulator which would mimic the variation in slant range on a shot-by-shot basis for a complete scan pattern. A random element on the slant range would simulate a wave height variation. Thus the wave height algorithm should extract a height equal to the standard deviation of the random perturbation.

The XYZ coordinate accuracy also depends on many parameters. The spot location on the surface is very sensitive to the scanner angles, α, β and δ, and to the attitude angles of the aircraft. The scanner angles will be measured accurately in the lab and can be checked in flight by scanning over calm water conditions with small roll and pitch. Once α, β and δ are verified, the roll and pitch can be checked as well. The yaw, or azimuth angle will have to be independently verified.

The attitude and scanner angles are doubly important because they are used to calculate the off-nadir angle, which in turn is used with the slant range to determine the altitude of the aircraft. The slant range time interval counter will be calibrated on the ground by using a hard target at a well-known distance. The surface marker offset value can be verified in this same measurement.

The transmitter alignment is unlikely to need adjustment but the transmitter/receiver alignment will be checked by visual observation of an overlap of the laser spot and a suitable spatial block in the receiver.

The absolute accuracy of the soundings will depend upon the aircraft positioning system. The APS can be continually checked for reasonable output and it should be possible to calibrate the system on the ground with the use of precisely located transponders. Of course, the positioning system fixes the position of the antenna on the aircraft while the spot location on the surface relative to the scanner mirror is calculated. The correct transformation of coordinates can be verified by measuring the offset distances and checking for proper behaviour of the scan pattern by inputting extreme offsets.

3.3 Maintenance and Spares

Maintenance of the HLBS will focus on care of the laser and the usual care given to electronic components. The laser optics and transmitter optics will have to be inspected regularly and cleaned when required. The receiver optics are less critical but should also be kept clean. The laser flashlamps will have to be changed at regular intervals.

A schedule of calibration based on manufacturer's suggestions should be followed for various electronic systems. In particular, the APS, the inertial reference system, and the digitizer are crucial for sounding accuracy.

A strongly recommended spare is an extra laser head, as they have a history of being problematic. Other spares could include a scanner motor, printed circuit boards and computer boards. A full list of spares will be developed in the detailed design phase.

APPENDIX 4 SYSTEM LABORATORY TEST PLAN

4.1 HLBS System Test Plan

The three main sub-systems to be tested in the lab are the:

Transceiver Subsystem (TRS),
Acquisition, Control and Display Subsystem (ACDS)
Data Processing Subsystem (DPS)

Each of these will be treated in the following sections of this document.

4.2 Transceiver Test Procedure

The function of the transceiver is to generate and transmit laser pulses, scan the laser beam, detect target return pulses, and generate appropriate signals required by other subsystems. These functions are performed by the three major subsystems of the transceiver: the laser transmitter, the scanner, and the receiver.

The laser generates pulses at a maximum repetition rate of 200 Hz. The scanner rotates at a speed of 1-5 Hz. This puts all the laser pulses/second in one scan or some portion thereof down to one-fifth of the laser pulses/second. For each laser firing the scanner outputs the appropriate scan angle and the receiver detects the optical return signal, outputs the waveforms to the digitizer and signal processors and generates the required timing and trigger signals.

4.2.1 Laser Transmitter

The parameters of the laser transmitter to be tested are described in the following list.

1. The maximum pulse repetition rate will be 200 Hz. The period of the pulses can be measured with an oscilloscope to be a minimum of 5-10 milliseconds.

2. The laser pulse energy can be measured at the output of the scanner with a suitable power/energy meter. The emitted energy should be 5 mJ at 532 nm and >2 mJ at 1064 nm.

3. A fast risetime of the laser pulse is essential for accurate depth determination, especially at shallow depths. This can be measured with a fast detector having a response time of about 2 nanoseconds.

4. The laser pulse must have a very short tail. The amplitude can be monitored with an APD and a logarithmic amplifier. The pulse amplitude should be <1% 20 nsec after the peak and <0.1% 50 nsec after the peak. In addition, any other pulses must be $<10^{-4}$ of main pulse.

5. The laser beam divergence should be adjustable in the range of 2 to 10 mrad. The divergence calibration will be verified and the beam wander over the range measured.

6. The laser will be tested for shock and vibration according to RTCA/DO-160B, Section 8, curve P and RTCA/DO-160B, Section 7.2, Operational Shocks, respectively.

7. The trigger delay of the laser will be measured.

4.2.2 Scanner

The scanner parameters to be measured in the lab consist of the following:

1. The fixed scanner angles α and β are crucial for accurate placement of the spots on the surface. The angle between the mirror normal and the rotating shaft, α, can be measured using a HeNe beam. The off-nadir angle of the rotating shaft, β, will have to be measured in conjunction with the inertial reference system.

2. The shaft rotation angle, γ, will be calibrated to a zero rotation reference point on the scan.

3. The reporting of laser shot number and its correlation with shaft rotation angle will be verified.

4. Two scanner modes will be selectable by the operator: scanning and profiling.

5. Correct plotting of the data will be confirmed by introducing artificial roll, pitch and yaw of the aircraft and displaying the resultant data.

4.2.3 Receiver

The receiver collects the backscattered light from the water surface and bottom and directs it to four detectors: the PMT and three APD channels. There are a multitude of parameters that will have to be tested to ensure the receiver is working properly. The most significant will be outlined below.

1. Detection of shallow depths requires very fast response times. The risetime of all four channels will be measured along with their respective amplifiers.

2. Control of the field of view, neutral density filter, central spatial block, and PMT mode (gated or not gated) will be calibrated and verified.

3. Manual control of three thresholds (the green discriminator, the constant fraction discriminator (CFD), and land/water discriminator), the range gate, and the PMT mode and PMT high voltage will be confirmed.

4. The control logic from the CFD, green discriminator and range gate settings will be verified with test waveforms. These waveforms will have known depth returns and will include such anomalies as spurious returns and infrared dropouts, among others.

5. The PMT propagation delay versus high voltage will be calibrated.

As the system goes into the detailed design phase, new parameters may arise which influence the system performance. A detailed test plan will include all such parameters.

4.3 Acquisition, Control and Display

Acquisition and storage of the digital waveforms and of the many parameters necessary for accurate XY placement are essential for system performance. As outlined in the conceptual design report, a preliminary list requires the storage of ~145 KBytes/sec, of which 100 KBytes/sec are the digitized waveforms and 34 KBytes/sec are the digitized video frames. Testing of the acquisition will consist of verifying the accurate tagging and storage of all finalized data items. As digitization of the waveform is crucial for accurate depth extraction, this will be tested thoroughly.

Automatic computer control of many parameters will be offered. These include the PMT mode, the range gating and the sounding density. Control of these features as well as manual control of these and other parameters will be verified.

There will be two displays: one for the operator and a second for the pilot. The operator will be presented with a series of nested menus which will allow the monitoring of all stored information and operator control parameters. In addition there are two modes of real time depth displays and a pre-flight sounding density display. The pilot will have the option of two different displays: one of a digitized map of the survey area and the other of a flightline tracking indicator. The integrity of all the personnel displays will be confirmed in the system test.

4.4 Ground-Based Data Processing

The primary purpose of the post-flight data processing is to provide accurate XYZ coordinates of the soundings.

The Z coordinate, or depth, extraction algorithm will be verified with digitized test waveforms. Many different waveforms exhibiting various features will be used. These features will include spurious returns, target returns above and below threshold, missing infrared return, etc. Depth bias corrections will also have to be tested. These will include such biases as the propagation bias (for which the estimated optical depth and instantaneous off-nadir scan angle must be known), the PMT propagation delay, the log amp delay, and the wave height correction, among others. The acquisition of necessary parameters and the calculations of these biases will be verified. It may not be feasible to test fully the waveheight correction algorithm in the laboratory but it will be tested as much as possible.

The calculation of the XY coordinate of the sounding will be verified by using many different test scenarios of aircraft and scanner orientation. For example, the roll, pitch and azimuth can be varied one at a time and the scan pattern display monitored to confirm its correct behaviour. The scanner angles, α, β and shaft angle, γ, will be verified by observing the dimensions of the egg-shaped ellipse at a measured distance from the mirror. The correction for the propagation bias error will also be confirmed by inputting various depths.

A figure of merit will be assigned to the final data which will depend upon the software flags set (for example, no infrared return would mean a less accurate depth). The exact weighting of the factors toward this confidence figure will have to wait until the detailed design.

APPENDIX 5 FIELD TEST PLAN

The flight tests of the HLBS system are intended to demonstrate operation from the helicopter platform, including system shakedown, optimization of system parameters, and evaluation of system performance. These tasks can be implemented in the following sequence:

1. System check-out in the laboratory.

2. Installation of the hardware in the aircraft.

3. Demonstration of system operation on the ground.

4. System calibration

5. System check-out in flight.

5.1. System Check-out in the Laboratory

Upon delivery of the HLBS system, the entire system should be set up and cabled together in a suitable laboratory environment. This should be done if convenience and time allow. Otherwise, the system can be immediately installed in the aircraft where it can be checked out on the ground. The reason for system setup and check-out in the laboratory is to provide a more convenient facility to test and debug the equipment after it has been shipped.

The HLBS transceiver and rack-mounted equipment will be cabled according to the installation and cabling drawings. The transceiver will be assembled with all components properly mounted in the frame.

The transceiver will be set up to allow the laser beam to exit the building and strike a suitable target located at a distance of 50-200 meters away. If this is not possible, the receiver will be tested using an optical test source.

When the entire system has been properly assembled and cabled, it can be powered up in order to verify that all systems are functional.

The tests can be divided into three groups: 1) transceiver tests, 2) data acquisition/control/display tests, and 3) ground system tests. The transceiver tests will verify the correct functioning of the laser, scanner and receiver. Testing of the data acquisition/control/display subsystem will verify the functionality of the airborne computer and all its interfaces to the various devices. Testing of the ground system will be accomplished by inputting known simulated data and verifying that the expected results are obtained. The system can then be tested as a unit by acquiring actual data from the airborne system, on tape, and feeding it to the ground system.

Following verification that the system is operational, the transceiver and electronics consoles can be installed in the aircraft.

5.2. Installation in the Aircraft

The HLBS system hardware will be installed in the aircraft according to the aircraft installation drawings. These will show the proper arrangement of the major components.

Following aircraft installation, the entire system will be interconnected according to the cabling drawings. When the system is properly cabled, all subsystems will be powered up using ground power, and the ground tests will commence.

5.3. Demonstration of System Operation on the Ground

Following installation of the hardware in the aircraft, the system will be tested on the ground, using auxiliary power. If sufficient testing can be carried out in the laboratory, prior to installation in the aircraft, then only a limited set of tests is required here.

The following tests will be performed on the ground to demonstrate system readiness for flight tests:

1.Transceiver Tests

- measurement of laser power
- scanner operation
- laser triggering
- transmitter/receiver alignment
- receiver response to laser-generated target return signals
- receiver electronics outputs
- time interval meter functionality

2. Data Acquisition/Control/Display Tests

- functionality of all sensors
- recording of data on cartridge tape
- control of all system parameters
- HLBS display functionality

3. Ground System Tests

- functionality of ground system using simulated data

These three series of tests can be carried out independently. The testing of the transceiver will require a suitable target for the laser beam to strike, and a mirror to direct the beam from the aircraft to the target.

The transceiver will be powered from auxiliary ground power, and all subsystems will be turned on to check that cable interconnections have been properly made and that all subsystems are functional.

The laser system will be checked to verify that it is functioning properly, and the laser power will be measured. The scanner system will be checked to verify that the rotation rate is correct and that it is generating the properly-timed trigger pulses for the laser. The scan pattern will be checked on the ground.

The laser beam will be deflected to a nearby solid target (50-200 m from the aircraft) via a suitable mirror placed underneath the scanner. The transmitter/receiver alignment will then be checked and optimized. The outputs of all detectors, and their corresponding logarithmic amplifiers, will be checked using the laser-generated target-return waveforms. All outputs of the receiver electronics will be checked. The slant-range time interval meter will be checked for correct output.

The data acquisition/control/display electronics will be powered from auxiliary ground power to verify system functioning and proper cabling. The functioning of the airborne computer will be tested using simulated input data. The data acquisition system will be tested to verify that it is receiving data from all sources and that the displayed parameters are correct. The display capability of the HLBS will be verified using simulated data input.

Sample data will be recorded by the data acquisition system on cartridge tape with all subsystems transmitting data, either real or simulated, to the airborne computer. The cartridges will then be read by the ground system to verify proper recording of the data.

At this point, when it is determined that the system is properly functional when powered from auxiliary ground power, a switchover will be made to aircraft power, with the helicopter fully powered and idling on the ground. This will test the functioning of the HLBS system in the electrical power and vibration environment of the aircraft.

5.4. System Calibration

System calibration will include verification of the laser firing angles using a test jig, and calibration of the positioning system, slant range measurement, and the surface marker offset in the lidar waveform.

5.5. In-Flight System Check-out

The tests performed in flight can be divided into the following phases:

1. Pre-takeoff check-out
2. Receiver tests
3. Data acquisition tests
4. System display verification

5. System control tests

6. Pilot guidance tests

The purpose of the pre-flight check-out is to ensure that there is no major system failure prior to takeoff. The laser and inertial reference systems will powered up from auxiliary ground power prior to takeoff. These systems can be checked out, to verify that they are functional, before switchover to aircraft power. Immediately after switchover, and before takeoff, all other subsystems will be turned on and checked for functionality.

During flight, system parameters such as laser power, scanner speed, PMT voltage, slant range, and aircraft roll, pitch, heading and ground speed will be monitored to ensure that the system is fully functional in flight.

The receiver will be tested by firing the laser into the water and observing the backscatter waveforms. The PMT gain will be set to its proper operating range, as determined by the ambient light level. The receiver electronics will be checked for proper signal triggering. During all of these tests, the outside ambient light conditions (sunny, cloudy, foggy, etc.) and water surface conditions (smooth, wavy, whitecaps, sun glint from water surface, etc.) will be noted.

Data acquisition will be verified by recording data from all sensors during a typical short flight, and examining the data with the ground system to verify that it has been properly recorded.

The HLBS operator display will be tested by flying over water having varying depth, and verifying that the color-coded depth display is correct. This will require the proper setting of the threshold in the real-time depth extraction algorithm, such that over deep water (no bottom return signal) the false alarm rate is very low.

System control will be tested in flight by varying the parameters of the system such as beam divergence, field-of-view, laser triggering, etc., and checking that they change accordingly.

The pilot guidance system will be tested by inputting specific flightlines into the system's computer and verifying that the pilot guidance displays are functioning correctly. The pilot will be required to first find a particular line with the aid of one of the guidance displays, and then follow the line as accurately as possible. This will include maintaining a given altitude and ground speed. The functionality of the guidance displays will be fully verified by changing aircraft altitude, speed and heading, and verifying that the displays are changing accordingly.

At this point the system will have gone through rigorous shakedown and debugging procedures, and will be ready to proceed with the demonstration of system performance, as described in the following Appendix.

APPENDIX 6 HLBS INITIAL FLIGHT TEST PLAN

TECHNICAL REPORT

HELICOPTER LIDAR BATHYMETRY SYSTEM (HLBS) INITIAL FLIGHT TEST PLAN

Dr. Richard D. Loft
Robert B. Wilkinson

Prepared for

OPTECH, Inc.
Downsview, Ontario, Canada

and

Coastal Engineering Research Center
U.S. Army Corps of Engineers
Waterways Experiment Station
Vicksburg, Mississippi

Prepared by

Applied Mathematics, Inc.
Gales Ferry, Connecticut

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SECTION I

INTRODUCTION

The objectives of this report are to present an initial plan for flight testing the OPTECH Helicopter Lidar Bathymeter System (HLBS) which demonstrates that the HLBS meets the performance requirements of references (a) and (b), to develop a set of criteria for evaluating the suitability of candidate test sites, and to develop criteria for estimating the scope of the proposed flight test in terms of time and cost.

I.1 BACKGROUND

Present acoustics (fathometer) and mechanical (lead-line) hydrographic surveying methods are slow and produce surveys which are dependent on the water level. The HLBS is an airborne laser-based system which will be capable of conducting rapid and accurate hydrographic surveys of waterways independent of the water level. This system is being developed by OPTECH, Inc. for the United States Army Corps of Engineers (USACE), Coastal Engineering Research Center (CERC), Waterways Experiment Station, Vicksburg, Mississippi.

The system uses a Nd:YAG laser, which produces an infrared wavelength pulse to accurately locate the water surface colinearly with a frequency-doubled blue-green pulse to detect the bottom. The distance traversed by each signal is determined by measuring the elapsed time between the emission and reception of the laser energy. A precise knowledge of the angle at which the energy was directed permits reconstruction of the surface (x,y) position, relative to the helicopter, at which the depth, z, was recorded.

I.2 ORGANIZATION OF THE REPORT

Section II discusses the proposed flight test objectives and their meaning in terms of the basic test parameters.

Section III establishes a set of criteria for evaluating candidate test sites.

Section IV develops the test design considerations.

Section V presents the proposed flight test procedures.

Section VI presents the scope of proposed testing in calendar days and a sample test schedule.

Section VII outlines logistical requirements for the flight test.

Section VIII discusses organization of test personnel.

Section IX describes data management requirements.

Section X discusses communications issues.

Section XI discusses navigation issues.

Section XII outlines safety concerns and requirements.

Appendix A provides a preliminary site analysis of the CERC field research facility at Duck, North Carolina.

SECTION II

HLBS FLIGHT TEST OBJECTIVES

The HLBS flight test has three major objectives. The first objective is to demonstrate that the HLBS meets the performance specifications. The second objective is to determine the limitations of system operation under a range of field conditions; that is, to determine the performance envelope of the system. The third objective is to demonstrate the HLBS to representatives of the U.S. Army Corps of Engineers.

This section describes the specifications which must be tested and the capabilities which must be demonstrated to achieve these objectives. The source for this information is reference (a). Section II.1 discusses the platform objectives. Section II.2 presents the HLBS performance objectives. Section II.3 discusses the environmental capabilities and limitations that must be demonstrated. Section II.4 discusses the data processing objectives of the flight test.

II.1 PLATFORM OBJECTIVES

The platform objectives are the following:

Compatibility

- Weight, size and power demand are compatible with a medium-sized commercial helicopter (e.g. the Bell 212 or Sikorsky S76).
- No major modifications to the helicopter are required.
- All modifications are compatible with FAA regulations.

Installation

- No more than six hours and two ground based technicians are required to install and calibrate the HLBS.
- No more than four hours are required to de-install and pack the HLBS.

Operation

- No more than one operator is required to operate the system onboard the helicopter.

II.2 HLBS SYSTEM PERFORMANCE OBJECTIVES

The HLBS system performance objectives are the following:

Maximum depth

- The maximum depth, z, at which the bottom can be detected is such that Kz = 3 to 4 in daytime and Kz = 4 to 5 at night, where K is the diffuse attenuation coefficient of the water.
  Note: All references to attenuation coefficients in this report are to diffuse attenuation coefficients.

Minimum depth

- The minimum depth that can be detected by the HLBS is in the range of 1.0 to 1.5 meters.

Vertical accuracy

- The vertical error relative to the aircraft is no more than ±0.2 meters in the topographic mode of operation and ±0.4 meters in the bathymetric mode of operation.
- The bottom can be located to an accuracy of ±0.3 meters relative to the water surface.

Relative horizontal uncertainty

- The horizontal position uncertainty of the surroundings relative to the aircraft is ±0.5 meters.

Positioning system

- The absolute position of the helicopter can be determined by one the following methods:
    - Microwave transponder system.
    - Inertial system.
    - Range-azimuth system.
    - Global Positioning System.

Sounding density

- Scanning mode provides a swath angle of 30 degrees and a grid spacing of 3-10 meters between soundings.
- Profiling mode operates satisfactorily.
- A maximum sounding frequency of 200 soundings/second is attainable.

Performance envelope

- Altitudes between 100 meters and 200 meters can be achieved within the specified survey accuracy and up to 1000 meters can be achieved with the accuracy restrictions relaxed.
- The system functions normally at helicopter speeds between 0 and 50 meters per second.

II.3 ENVIRONMENTAL OBJECTIVES

The HLBS flight test should investigate the environmental factors which will affect performance of the system. Environmental factors include:

- sun angle and elevation effects,
- the effect of wave height on system depth accuracy,
- degradation effects due to surf and whitecaps, and
- the effect of bottom type and irregular bottom topography.

II.4 DATA PROCESSING OBJECTIVES

The data processing objectives of the flight test include demonstrating:

- automated data reduction of the airborne data to an x,y,z survey data base,
- software provisions for quality checking, smoothing and editing data,
- hard-copy capability, and
- data processing time no more than five times greater than the data acquisition time.

SECTION III

FLIGHT TEST SITE CRITERIA

Certain criteria should be met by the candidate test site in order to achieve the HLBS flight test objectives in Section II. Since some of these criteria are seasonally dependent, this section also examines the factors which could affect scheduling of the flight test. The environmental conditions which should prevail are outlined in Section III.1. The logistical support capabilities required at the test site are discussed in Section III.2. Finally, the ground-truth data required is discussed in Section III.3.

III.1 ENVIRONMENTAL FACTORS

The environmental factors which affect the desirability of a candidate test site fall into two main classes: seasonally independent and seasonally dependent.

Seasonally independent factors are:

Bottom topography. The test site should have a number of different bottom topographies, including:

- flat bottom,
- sloping bottom, and
- irregular bottom.

Bottom depth. The bottom depths at the test site should include shallow regions with 1-2 meter water depths and deep regions with depths corresponding to $Kz = 6$, where K is the attenuation coefficient.

Bottom type. The bottom at the test site should present a well-defined optical boundary. For this reason, sand and gravel are preferable to a muddy bottom. Also, a bottom with a high reflectivity is desirable for ease of detection.

The extent of the seasonal variations of environmental conditions is dependent on the test site location. Therefore, this discussion is limited to a description of the optimal conditions for testing. The scheduling of the flight test for a particular site must be determined based on meteorological and oceanographic data collected locally (see Appendix A).

Environmental factors which are seasonally dependent are:

Water clarity. Shallow water clarity is sensitive to the water temperature/density profile and to the amount of wave action. The highest visibility is expected in warm water with no wave action. This expectation is realized experimentally (reference c).

Wave height. In addition to decreasing water clarity, large wave heights adversely impact bathymetric survey efforts in several other ways. Depth measurement errors are increased and the bottom itself may change due to the rapid deposition and erosion of material. For these reasons, it is desirable to avoid such conditions, when conducting the flight test.

Weather conditions. The weather conditions during the flight test should be compatible with helicopter and small boat operations.

It follows from this list of environmental factors that, for test sites in northern temperate climates, the summer months are most likely to provide optimal conditions for performance of the initial HLBS flight test. Also, in northern subtropical climates, more months of acceptable conditions are expected to be available than in northern temperate climates.

III.2 LOGISTICAL SUPPORT CAPABILITIES

Certain logistical support capabilities will be required at the test site and the surrounding area. These capabilities include:

- helicopter staging facilities,
- access roads,
- office space,
- electrical power, telephones, and
- lodging.

The single most important logistical support requirement is the helicopter staging facility. This facility should have the capability to secure, maintain and operate either the Bell 212 or Sikorsky S76 helicopter. Optimally, such services would be available at the test site to avoid long transit times. Alternatively, a small airport nearby could provide these services.

It is important to emphasize the need to minimize transit time between the staging area and the test site. The effect of transit time on flight test efficiency can be examined by calculating the helicopter time on station per sortie.

If t_E is the endurance time of the helicopter (assumed to be velocity independent), v_T is the transit velocity and D_T is the transit distance, then the time actually spent taking data per sortie, t_D, is

$$t_D = t_E - 2D_T/v_T \tag{III-1}$$

If N helicopter sorties are performed per flight day, the number of flight days required for each hour of testing, N_{FD}, is

$$N_{FD} = \frac{1}{N\,(t_E - 2D_T/v_T)} \tag{III-2}$$

Assuming values for the parameters of, $v_T = 100$ mph, $t_E = 2.5$ hrs, $N = 2$, based on the Bell 212 helicopter characteristics, (reference d), a plot of N_{FD} versus the transit distance D_T can be made. This is shown in Figure III-1. This plot is useful for two reasons. First, it can be used to compare the relative efficiency of conducting the same flight test at two different locations. Second, Figure III-1 is useful for estimating the total length of time required to complete a proposed series of tests (see section VI).

The existence of adequate access roads at the test site is important to the ground-based support activities of the flight test. These activities include the positioning of navigation aids, the surveying of objects in the water and on the land to determine ground-truth, and the establishment of a test control site overlooking the test area.

Office space is required during the test for the control of the flight test, processing of the data collected, and for administrative support. A room large enough to conduct preflight briefings and planning meetings is highly desirable. The lack of such office space can be compensated by the acquisition of a trailer on a temporary basis, but this is likely to increase the cost of the test.

The flight test office, and the associated data processing activities, will require electrical power and telephone service. Electrical power can be provided by a portable generator in the absence of improvements, but again at increased cost. Telephone service is required.

The flight test participants will require lodging and dining facilities. If a long commute is necessary between these facilities and the test site, the costs associated with car rental will be increased. It should also be noted that the availability and cost of lodging may be seasonally dependent in some areas.

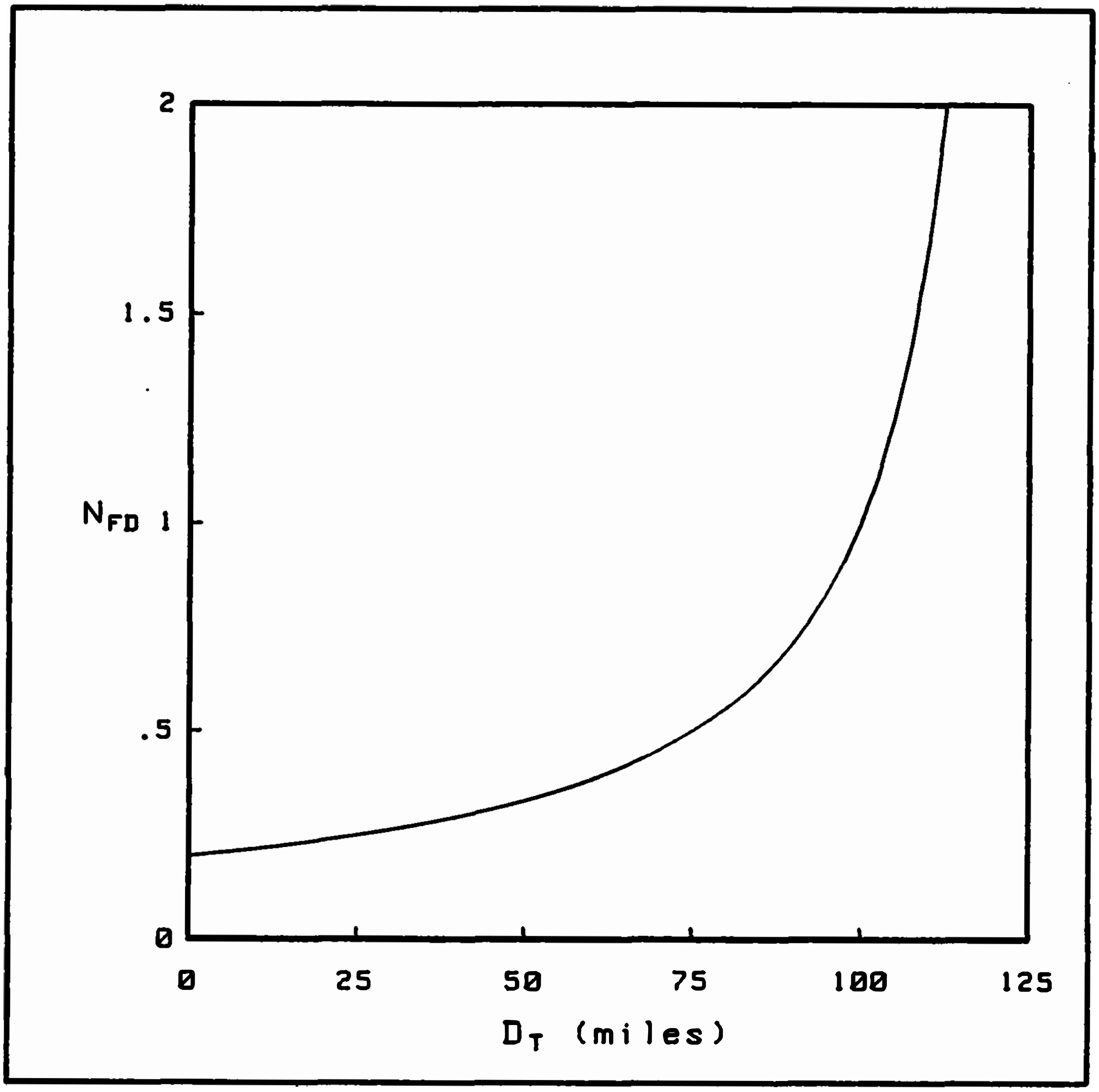

Figure III-1. Variation of the number of flight days per flight test hour, N_{FD}, with helicopter transit distance, D_T, for a Bell 212 helicopter.

III.3 GROUND-TRUTH DATA

The following test site survey data should be available prior to and during the HLBS flight test.

- Topography/bathymetry. It is essential that up-to-date comprehensive topographic and bathymetric survey data be available for the test site. If possible, the depth and position errors of this survey should be much less than the HLBS performance goals in Section II. It is also desirable that the bottom topography be stable during the flight test. To check this, a ground-truth survey should be conducted both prior to and after the test.

- Attenuation coefficient. The attenuation coefficient, K, must be known during the test in order to validate the HLBS maximum detection depth. For an accurate determination of bottom detection performance, K must be measured as a function of depth. Also, the value of K should be obtained at several locations to determine the position dependence of the attenuation coefficient. These measurements should continue throughout the test, but should be made most frequently during the maximum detection depth tests.

SECTION IV

FLIGHT TEST DESIGN CONSIDERATIONS

The proposed tests of the HLBS system should efficiently address the flight test objectives, while at the same time conform to the principles of good experimental design, such as:

- isolation of the relevant variables,
- control of other system variables, and
- exploring first the areas of parameter space that establish operational limits on system performance.

Efficiency in test design is necessary because helicopter flight operations are expensive and often unpredictable in terms of both time and cost.

IV.1 PARAMETER DEFINITION

There are three classes of variables which affect the performance of the HLBS: helicopter, system, and environmental. The variables in each category are:

- Helicopter
  - helicopter altitude, H
  - helicopter velocity, v
- HLBS system
  - Laser energy, E
  - Laser pulse repetition frequency, f_L
  - Laser wavelength (blue-green), λ
  - Scan frequency (mirror nutation frequency), f_S
  - Off nadir angle, θ
  - Beam divergence, d_B
  - Spot diameter, $D_S = Hd_B/\cos \theta$
  - Receiver telescope field-of-view, d_R
  - Spatial block position (in/out)

  - Photodetector type (blue-green), i.e., photomultiplier tube (PMT) or avalanche photodiode (APD1)
  - PMT voltage setting, V_{PMT}
  - Receiver aperture area, A
  - Spot overlap factor, F
- Environment
  - Bottom depth, z
  - Bottom reflectivity, ρ_B
  - Wave height, H_w
  - Lighting conditions, S_λ, (ambient spectral radiance at wavelength λ),
  - Seawater attenuation coefficient. K

Because of the large number of variables, it is essential to limit the number of combinations which must be investigated in determining the performance of the HLBS.

IV.2 ISOLATION AND CONTROL OF VARIABLES

For each of the performance objectives of the flight test, the variables affecting performance can be separated into two classes: test matrix variables and control variables. Test matrix variables are defined to be the small set of helicopter, system and environmental parameters which critically influence the performance characteristic under study. These variables should be studied in conjunction with other variables in a grid of test points called a test matrix. Control variables are defined as variables which should be held fixed during these specification tests. Control variables can be included in the flight test and studied in isolation (i.e. by holding all other variables fixed) as time permits.

It is also necessary to determine appropriate composite variables, such as the dimensionless quantity, Kz, which directly influence system performance. The choice of appropriate composite variables effectively reduces the size of the test matrix which must be implemented.

From section II.2, four basic measures of HLBS performance will be investigated:

Maximum bottom detection depth (as parameterized by Kz),
Minimum bottom detection depth,
x,y,z survey accuracy, and
H-v performance envelope.

Each of these measures will now be considered, and the relevant parameters identified.

- Maximum bottom detection depth. The parameters which play a role in determining the maximum detection depth are:

  H, altitude of the helicopter,
  E, the laser pulse energy,
  d_R, the receiver telescope field-of-view,
  S_λ, ambient spectral radiance, and
  ρ_B, the bottom reflectivity.

  Of course, other parameters could affect the system depth performance. For example, the signal-to-noise ratio is a sensitive function of the filter bandwidth, $\Delta\lambda$. Such parameters are design parameters, and are assumed to be fixed throughout the flight test.

  Of the five variables, which affect detection depth, three should be measured and held constant (E, S_λ, ρ_B) and two varied (H, d_R). In the case of spectral radiance, two values of S_λ; corresponding to daylight and nighttime, are planned to be investigated (see Section II.2).

- Minimum bottom detection depth. The minimum detection depth capability is expected to primarily be a function of the type of photodetector used, PMT or APD.

- x,y survey accuracy. The measurement uncertainty of the x,y position of a spot relative to the helicopter is expected to be a function of:

  H, altitude,
  z, water depth, and
  D_S, spot size.

  Since the contribution to the position error from altitude is the most significant, the test matrix for this test should primarily investigate different H, D_S combinations.

- z survey accuracy. The measured depth survey uncertainty is expected to depend on the wave height and on the depth z. These two parameters should be varied during the z position accuracy tests as conditions at the test site permit.
- H-v performance envelope. The overall performance envelope will be determined by varying altitude between 100 meters and 1000 meters and by varying helicopter speed between 0 and 50 meters per second.

SECTION V

TEST PROCEDURE DESCRIPTION

This section provides a detailed description of the flight test procedures. These procedures are designed to accomplish the objectives described in Section II and to incorporate the test design considerations discussed in Section IV.

For each test, the following topics are discussed:

- the purpose of the test,
- materials required including site conditions, surveys, and support services,
- procedures which address the methodology of the test, test matrix size; and special safety, communications and data collection concerns, and,
- data analysis issues including the expected data set, the expected results, and the best formats for presenting results.

The test procedures are divided into two groups: ground-based tests, which are discussed in Section V.1, and flight test, which are described in Section V.2.

V.1 GROUND-BASED TESTS

It is desirable to demonstrate the high portability anticipated for the HLBS. For this reason, a mobilization and demobilization demonstration will be performed during the test. These ground-based demonstrations are discussed in the sections which follow.

Step-by-step procedures for the installation and calibration of HLBS will be promulgated separately by OPTECH, Inc.

V.1.1 Mobilization Demonstration

Purpose. The purpose of the mobilization demonstration is to determine the amount of time and the number of technicians required to install and calibrate the HLBS in the test helicopter. The results of this demonstration will be used to evaluate compliance of the HLBS with the mobilization target of no more than six hours of installation time and no more than two ground-based technicians.

Personnel/materials required. The materials required to complete the mobilization test include:

- the modified test helicopter,
- the HLBS system in the packing crates,
- all necessary tools and equipment for installation and calibration of HLBS,
- two trained technicians,
- installation/calibration observer familiar with system.

Procedure. The observer will monitor the mobilization demonstration and perform the following tasks:

- The observer will record the start time when work begins on the system. This work includes modification of the helicopter, if required, unpacking of shipping containers and deployment of testing equipment.
- The observer will monitor, without impeding, the installation and calibration procedures noting the times of critical steps, problems encountered and personnel working on the system.
- The completion time will be recorded when the system is calibrated and ready for flight operations.
- After the mobilization demonstration, comments will be solicited from the participants in order to determine methods to improve the installation and calibration procedures.

A dry run prior to the HLBS deployment is advisable to ensure that all required tools and equipment are available and that all participants are familiar with their mobilization tasks.

Safety. Safety issues associated with this demonstration include:

- laser safety (some lasing on the ground may be required during this procedure),
- personnel safety - participants should follow normal work practices to avoid injury during the demonstration.

Data analysis. The following analyses are to be undertaken:

- Observer(s) and participants will meet at the end of the mobilization to review data collected during the demonstration and to provide comments and recommended procedural changes.
- Comments and recommended procedural changes will be reviewed and procedures revised as necessary based on demonstration results.
- Results of the mobilization demonstration will be incorporated in the flight test report.

V.1.2 Demobilization Demonstration

The demobilization demonstration will be identical to the mobilization demonstration of Section V.1.1, except that the goal will be to demonstrate that the HLBS can be removed and packed for shipment within four hours.

V.2 FLIGHT TESTS

This section describes the flight tests which will be conducted as part of the evaluation of HLBS performance. The tests will not necessarily be performed in the order presented. The flight tests are the following:

- shakedown test (V.2.1),
- daytime maximum/minimum detection depth test (V.2.2),
- nighttime maximum/minimum detection depth test (V.2.3),
- topographic and bathymetric uncertainty test (V.2.4),
- horizontal uncertainty test (V.2.5),
- sun angle tests (V.2.6),
- beach survey demonstration (V.2.7).

All flight tests will have certain characteristics in common. The minimal set of prerequisites required before the beginning of any flight test will include:

- preflight evaluation of current meteorological and oceanographic data, including:
  - wind velocity
  - wave height
  - sea water attenuation coefficient.
- completion of the pretest brief and preflight checklists,
- a fully manned and operational control center,
- communications checks with all participating units completed,
- helicopter positioning system in operation, and
- clearance from the test site safety officer,
- check operation of data recording systems.

V.2.1 The Shakedown Flight Test (Test 1)

Purpose. The purposes of the shakedown flight test are to:

- demonstrate the two scanning modes of operation; survey and profiling,
- demonstrate the ability of the guidance system to provide real-time guidance information to the pilot so that pre-defined survey lines, defined by the HLBS operator(s), can be flown,
- demonstrate the ability of the HLBS to discriminate between water and land,

- test the in-flight operation of HLBS components including
    - the laser transceiver, optics, and detectors,
    - the real-time displays,
    - the automatic data acquisition system,
    - the helicopter positioning system,
    - the laser altimeter, and
    - the inertial reference system,
- demonstrate HLBS operation at a maximum speed of 100 kts (50 m/s),
- evaluate and correct any problems discovered, and
- familiarize the flight crew and other test participants with the test area and data-taking procedures.

Prerequisites. No additional material or personnel are required to establish the prerequisites for the flight test discussed in section V.2.

Test Site Description. Surveys will be flown on two small sections of the test site. The set of survey lines will be of limited number, and the dimensions of the test area of limited size, in order to minimize the amount of time spent on this phase of the testing. Survey areas will be approximately 500 meters x 500 meters. With a survey line length of 500 meters a helicopter altitude of 100m and a speed of 30 knots, the helicopter can survey this area by flying six survey lines in approximately 5 minutes.

The bottom topography for the first test area, designated 1.1, is not critical, but a gently sloping bottom, with depths well within detectable range of the HLBS, would provide data useful for planning the next phase of testing, the maximum detection depth test.

The second test area, 1.2, should include both land and water. The land and bottom topography of this area is not critical to the test.

Procedure.

(1) Prior to arrival at the test site, 1.1, the flight test HLBS operator(s) will input a predefined set of survey lines into the helicopter guidance system.

(2) Upon arrival at the test area, and upon receipt of permission by the test site safety officer, laser energy will be emitted from the helicopter by the HLBS.

(3) The flight test HLBS operator(s) will verify proper operation of the HLBS system, including:

- the laser transceiver, optics and detectors,
- the real time displays,
- the automatic data acquisition system,
- the helicopter positioning system,
- the laser altimeter, and
- the inertial reference system.

Time will be allocated during this step for optimization of system parameters and for the evaluation and correction of any problems discovered. It is anticipated that detection of the bottom will be achieved during this phase of the test. After the system has been tested for proper operation, a laser pulse repetition rate (sounding rate) of 200 soundings/second will be established.

(4) Using the guidance information, the pilot will execute the survey pattern several times, holding altitude fixed, and varying speed and mirror nutation frequency to change the sounding density. During this phase of testing, a maximum survey speed of 100 kts will be attempted.

(5) The profiling mode will be demonstrated by repeating the same survey pattern at a fixed altitude and speed after switching to profiling mode.

(6) The flight test HLBS operator(s) will input the survey pattern for the second test area, 1.2, which overlaps land and water, into the guidance system.

(7) Steps (4) and (5) will then be repeated for test area, 1.2, once in survey mode and once in the profiling mode.

(8) The laser transceiver will be secured, along with the data acquisition system.

Safety. No special safety issues, other than those normally encountered in flight test operations and described in Section XII, are expected during this test.

Data analysis. The daily quick-look analysis of the data acquired during this test will be conducted immediately after the test. The objective of this analysis will be to produce a brief, informal data package which summarized the results of the first day of flight testing. This summary will include

- missing data channels or gaps in the data record,
- survey summaries, preferably in the form of bathymetric contour plots of the area surveyed, and
- any depths or locations for which soundings could not be obtained.

V.2.2 Daytime Maximum/Minimum Detection Depth Test (Test 2)

Purpose. The purposes of the daytime detection depth test are to:

- determine if the HLBS meets the design specification for maximum detection depth of $Kz \geq 3$ in daytime, where K is the seawater attenuation coefficient,

- determine if the HLBS meets the design specification for minimum detection depth of 1.0 to 1.5 meters, and
- demonstrate performance limitations associated with increasing helicopter altitude up to a maximum of 1000 meters.

This test should be conducted in either morning or late afternoon.

Prerequisites. In addition to the usual flight test prerequisites, this test will require:

- determination of the pulse energy E of the laser transmitter,
- a detailed ground-truth bathymetric survey of the test area,
- samples of the bottom material taken at several points in the area.

Test area description. Two distinct test areas may be required to perform this test, depending on the local characteristics of the test site.

The first area, 2.1, should have a gently sloping (1-2%) bottom, with depths such that the parameter, Kz, ranges between 2 and 6 as one proceeds from the shallow water boundary of the area to the deep boundary. The reflectivity of the bottom should be relatively uniform over the entire test area. The lateral dimension of the test area need only be large enough to accommodate navigation errors associated with the helicopter. As an aid to the pilot in lining up the passes on this area, range buoys should be located at either end.

The second test area, 2.2, should be located in a region of calm, shallow water with depths ranging between 0-2 meters. Once again, a gently sloping bottom is preferable. This area will be used for the minimum detection depth test.

Procedure.

(1) After obtaining clearance from the test site safety officer to proceed, the helicopter will activate the HLBS in the profiling mode. The pulse repetition (sounding) rate of the laser will be established at 200 soundings/sec. The spot size will be minimized by reducing the beam divergence to its minimum value (expected to be 1 mrad.).

(2) The helicopter will attain the altitude, H, and receiver field of view, d_R, combination to be used during the run.

(3) The helicopter speed during the run will be such that the dimensionless parameter, Kz, increases at a rate of no more than 2 units per minute during the test.

(4) The helicopter will line up on the buoys marking the shallow end of the maximum detection depth test area, 2.1, and traverse the test area from the shallow end to the deep end.

(5) The flight test HLBS operator(s) will monitor the real-time bathymetric displays to determine the point at which the bottom is lost. The time and depth at which this occurs will recorded on a log sheet in the helicopter for each run.

(6) The helicopter will reverse direction after flying the complete test area, and proceed to the shallow end of the area maintaining the same speed, altitude and HLBS system parameters. The flight test HLBS operator(s) will monitor the real-time bathymetric displays to determine the point at which the bottom is regained. The time and depth of this event will be recorded on a log sheet in the helicopter.

(7) Steps (2) - (6) will be repeated for each altitude and receiver field-of-view combination in the test matrix. Assuming that each

run takes 5 minutes, a series of 4 altitude and 3 field-of-view combinations can be completed in 1 hour of flight time.

(8) The helicopter will next proceed to the minimum detection depth test area, 2.2.

(9) The photomultiplier (PMT) detector will be selected initially as the shallow water detector.

(10) The helicopter will attain the altitude required during the next run.

(11) The helicopter speed will be such that the depth changes at a rate [6~ less than 2 meters per minute.

(12) The helicopter will fly from the deep (2 meters) end to the shallow (0 meters) end of the test area by lining up on the test area marker (either stakes or buoys).

(13) Steps (10) through (12) will be repeated for all altitudes in the test matrix.

(14) The avalanche photodiode detector (APD) will then be selected as the shallow water detector.

(15) Step (13) will be repeated. This will complete the data collection effort for the daytime detection depth test.

Safety. No special safety concerns exists for this test beyond those discussed in Section XII.

Data analysis - maximum detection depth. Assuming that Kz increases linearly from 2 to 6 along the length of the test area, the spot-to-spot change in Kz is expected to be approximately 2 x 10^{-4}. If one defines the Kz value at which the signal is lost (or regained) as the one at which the probability of obtaining a sounding is 0.5, then some binning of the test data will be required to measure this probability. The uncertainty in the derived probability decreases roughly according to 1 divided by the square root of N, where N is the number of soundings in each data bin. Thus, to estimate this probability with an uncertainty of 10% requires bins of 100 data points. Therefore, one can expect to be able to determine the limiting Kz to an uncertainty of ±.02. This uncertainty is more than adequate to establish compliance with the daytime performace objective. The data can be presented in a probability vs. Kz plot.

Because the data at various H and d_R values will have been acquired, the dependence of the limiting Kz value on these two variables can be studied. These results can be presented in the form of Kz vs. H and Kz vs. d_R plots. Also, the difference between the deep to shallow and shallow to deep values of Kz can be contrasted by analyzing the reverse legs of the data collection runs.

Data analysis - minimum detection depth. The data analysis technique which should be used to determine the minimum detection depth is the same as presented above. An uncertainty in this depth of ±.02 meters can be expected.

The results of this analysis should be presented in a format which contrasts the performance of the two detectors and permits determination of the sensitivity of this performance characteristic to altitude.

V.2.3 Nighttime Maximum/Minimum Detection Depth Test (Test 3)

Purpose. The purpose of the nighttime detection depth test will be the same as the daytime test (see Section V.2.2) except that the maximum detection depth at night will be evaluated against a specification of $Kz \geq 4$.

Prerequisites. In addition to the prerequisite described in Section V.2.2, the following items must be provided:

- lighted markers for designating the test areas, and
- lighting at the helicopter emergency landing area.

Test site description. The test sites for this series of tests will be the same as those described in Section V.2.2. For the purpose of consistency, the maximum detection depth test site, 2.1, will be relabeled, 3.1 for the nighttime test, and, similarly, site 2.2 will be relabeled, 3.2.

Procedure. The procedure will be the same as described in Section V.2.2.

Safety. Nighttime helicopter operations will present special safety concerns which must be fully addressed prior to the flight test. In particular, night adaptation, minimum flight altitudes and emergency landing sites must be reveiwed by the participants.

Data analysis. The data analysis will follow the procedures described in Section V.2.2.

V.2.4 Topographic and Bathymetric Vertical Uncertainty Test (Test 4)

Purpose. The purposes of the topographic and bathymetric vertical uncertainty test will be to:

- determine if the HLBS meets the required topographic vertical uncertainty specification of ±0.2 meters relative to the aircraft,
- determine if the HLBS meets the required depth uncertainty of ±0.3 meters relative to the water surface and ±0.4 meters relative to the aircraft, and
- decouple the vertical error from the x,y position uncertainty of the aircraft.

Prerequisites. In addition to the usual flight test prerequisites, this test will require:

- detailed ground-truth bathymetric survey(s) of the test area(s),
- a detailed topographic survey of a small test area,
- reflective boundary markers along two sides of each designated test area. On land, these could consist of strips of white material and, in the water, a line of white floats could be used.

Test area description. Three distinct test areas will be required to perform this test. These sites will be designated 4.1, 4.2, 4.3. Test site 4.1 will be located on land and will be a small area approximately 30 x 30m in size, which has been surveyed and found to be flat. Test site 4.2 will be located in shallow water and will be similar in size to site 4.1. Test site 4.3 will be located in water of depth near to the maximum detection depth of the system and will also be similar in size to site 4.1. Sites 4.2 and 4.3 will also be areas which have found to be flat.

The reason that all three of these sites must be flat is that a flat bottom permits decoupling the vertical error from the horizontal error, provided the horizontal error does not cause the soundings to drift out of the flat region. Thus, the test area only needs to be big enough to ensure that this does not happen.

The variation allowable in these surveys will be such that the standard deviation of the points of the ground truth survey is less than one half of the standard deviation goal for the vertical measurement. Thus, the test area for test 4.2 must have variations survey depth of 0.15 meters or less. This "flatness" requirement will ensure that the contribution of bottom irregularities to the measured error is less than twenty percent and that the errors inherent in the HLBS are dominant.

Procedure. The helicopter will proceed to test area 4.1.

(1) After obtaining clearance from the test site safety officer, the helicopter will activate the HLBS lidar in the profiling mode. The pulse repetition rate of the laser will be set at 200 soundings/sec, and the spot size will be minimized by reducing the beam divergence to its smallest value.

(2) The helicopter altitude will be established at 200 meters and the speed at 10 knots.

(3) The pilot will make several passes over the test site with the helicopter track oriented perpendicular to the two white boundary markers.

(4) The flight test HBLS operator(s) will monitor the real-time display to ensure that the spot pattern is passing over the test area, noting the start/stop time of each pass.

(5) The helicopter will proceed to water test area 4.2 and repeat steps (2) through (4). During this series of runs, the flight test HLBS operator(s) will use the real-time display to verify that the bottom is being detected.

(6) Step (5) will be repeated at test area 4.3. This concludes the vertical accuracy test. This test will be repeated during different wave-height conditions as time and opportunity permit.

Data analysis. At ten knots, the helicopter will pass over a 30 meter wide test area in about 6 seconds. During this time approximately 1200 soundings will be collected. This sample set size will permit accurate determination of the uncertainty of the measurement.

The reflectivity contrast of the boundary markers will serve as "flags" in the data set, marking the beginning and end of the flat test area.

Locating these flags in the data set will be facilitated by the times recorded by the HLBS operator for each run.

For the depth uncertainty test, systematic effects of the wave action will be compensated by using inertial reference system data for the helicopter. Finally, the bathymetric or topographic uncertainty of the HLBS, σ_{HLBS}, can be obtained in the following manner. Assuming that σ_{HLBS}, and the variance of the bottom determined by the ground truth survey, σ_B, are independent, the total error of the measurement during the flight test σ_{TOT} is:

$$\sigma^2_{TOT} = \sigma^2_{HLBS} + \sigma^2_B .$$

Since σ_{TOT} and σ_B are known, σ_{HLBS} can be inferred

$$\sigma_{HLBS} = \sqrt{\sigma^2_{TOT} - \sigma^2_B} .$$

The results of this experiment are expected to produce σ_{HLBS} for each of the test areas, with values available for the different sea state conditions encountered during the test.

Safety. No additional safety considerations are required for this test.

V.2.5 Horizontal Uncertainty Test (Test 5)

Purpose. The purpose of the horizontal uncertainty test is to measure the altitude dependence of the horizontal error of the HLBS relative to the aircraft. The horizontal error goal is ±0.5 meters.

Prerequisites. In addition to the usual flight test prerequisites, this test will require the following:

- The test area must contain several distinct topographic irregularities at least 1-2 meters in size. If adequate irregularities cannot by located, barrels or other distinctive shapes must be positioned within the area.
- A detailed survey of the angles and distances between the topographic irregularities will have to be made. The x,y position errors of this survey must be less than 0.1 meters.

Test area description. The area should be reasonably flat and approximately 100 x 100 meters in size. This test area will be designated as 5.1.

Procedure. The helicopter will proceed to test area 5.1.

(1) After obtaining clearance from the test site safety officer, the helicopter will activate the HLBS lidar in the survey mode. The flight test HLBS operator(s) will establish the highest density survey pattern attainable under these conditions by adjusting the mirror rotation frequency and laser pulse repetition frequency. The spot size will be minimized by reducing the beam divergence to its smallest value.

(2) The helicopter altitude will be at 100 meters and a speed of 10 knots will be maintained.

(3) The helicopter will survey this area repeatedly, approaching from several different directions.

Note: The number of approaches required to obtain nearly simultaneous lidar returns on two or more irregularities will depend on the number of irregularities and on the survey capabilities of the HLBS.

(4) The helicopter will then proceed to the next altitude at which measurements are to be conducted.

(5) Steps (3) and (4) will be repeated until all altitudes in the test matrix have been completed.

Safety. No additional safety concerns, beyond those discussed in Section XII, exist for this test.

Data analysis. If one can simultaneously measure the position of two points relative to the helicopter using the HLBS, it is possible to infer the distance between them. Since this distance is accurately known from survey measurements prior to the test, the error in this inferred distance can be determined if a large number of simultaneous measurements are obtained. The error in this inferred distance can be related to the helicopter. For example, assuming that relative x, and y errors are identical, the inferred distance error will be larger than the single point error by a factor of the square root of 2. If relative x and y errors are not identical, then the relationship between inferred distance error and single point error will be orientation dependent. Hence, by studying several different orientations of the survey relative to the test area irregularities, both errors can be measured.

The expected results will be the single point relative standard deviations as a function of altitude. With these results, it will be possible to assess the HLBS capability to achieve the horizontal error goal.

V.2.6 Sun Angle Test (Test 6)

Purpose. The purpose of the sun angle test is to determine the effect of the sun azimuth and elevation angle on the performance of the HLBS, as measured by the maximum detection depth.

Prerequisites. In addition to the usual flight test prerequisites, this test will require:

- determination of the pulse energy, E of the laser transmitter,
- a survey of depth profiles for the attenuation coefficient from several points in the area,
- a detailed ground-truth bathymetric survey of the test area,
- wave angle measurement (relative to shore) during the test, and
- samples of bottom material from several points in the test site.

Test area description. The test area will be an expanded version of test 2.1 (see Section V.2.2). The survey will be performed in the region in which $2 > Kz > 6$, along a line perpendicular to the depth contours. The lateral dimension will be extended to 100 meters on each side. This test area will be designated as 6.1.

Procedure. The procedure followed will be the same as the maximum detection depth procedure in Section V.2.2, (steps (1)-(6)) with the following changes:

- The altitude will be fixed at 100 meters.
- The field-of-view of the receiver will be fixed.
- The scan mode will be survey.

The entire procedure will be repeated for three times of day:

- morning (sun elevation < 30 degrees)
- mid-day (sun elevation > 60 degrees)
- evening/late afternoon (30 degrees < sun elevation < 60 degrees)

Safety. See Section XII.

Data analysis. The sun azimuth angle will be different for each spot in a given scan. The elevation angle of the sun will vary between three values during the three survey runs which constitute this test. From the data acquired, it will be possible to construct curves displaying the maximum detection depth versus sun angle and elevation. The wave angle data, collected as a prerequisite for the test, will be useful in interpretation of these results in terms of sunlight reflection effects.

V.2.7 Beach Survey Demonstration (Test 7)

Purpose. The purpose of this test is to demonstrate the ability of the HLBS to survey across the land-water boundary while performing a beach survey. If possible, an assessment will be made of the effects of changing surf height and foam line width.

Prerequisites. In addition to the usual flight test prerequisites, this test will require:

- a topographic and bathymetric survey of the test area to establish ground truth, and
- a wave height sensor to record wave height data during the demonstration.

Test area. The test area will consist of a 500 meter wide region, oriented perpendicular to the depth contours extending from well inland to well beyond the surf zone. This area will be designated as 7.1. The area should also include some irregular features.

Procedure.

(1) Prior to arrival at the test site, the HLBS operator(s) will select the optimal HLBS parameters (detection type, field of view, altitude, speed, etc.) for the survey. The HLBS operator(s) will then enter the pre-determined survey pattern into the guidance control system.

(2) After obtaining clearance to proceed, the helicopter will activate the HLBS in the survey mode.

(3) The pilot will fly the test area following the track established by the HLBS operator(s).

(4) After completion of the survey, the HLBS operator(s) will produce a new survey pattern by adjusting the beam divergence to change the spot diameter, by changing the altitude to adjust the cross-track separation, and by changing the velocity to adjust the in-track separation.

(5) Steps (3) and (4) will be repeated until a satisfactory set of surveys is acquired for test area 7.1.

(6) The entire procedure (steps (1) through (5)) will be repeated if the wave-height conditions change and flight time permits.

Safety. No additional safety requirements exist for this test, beyond those described in Section XII.

Data analysis. This demonstration will provide several surveys of the same area, taken within a short period of time. These surveys will provide a data base extending across the land-water interface which can be used to evaluate the effectiveness of HLBS in a beach surveying mode. Of particular interest is the extent to which the surf zone causes a loss of data. The data base will also permit determination of the most effective survey pattern, in terms of density and spot size. The data presentation format for this test will include contour plots and comparisons of the different survey profiles for single common survey lines.

SECTION VI

FLIGHT TEST SCOPE

The goals of this section are to make a preliminary estimate of the length of the test in calendar days and to develop a preliminary test schedule to illustrate the manner in which the test will be performed. In Section VII.1, a specific number of runs are assumed for each test, and estimates of the flight time per run are used to calculate the total required test time. Test time is converted into flight time by including transit time and efficiency factors. Calendar days required are then calculated. Finally, Section VI.2 presents a preliminary flight test schedule based on these estimates.

VI.1 FLIGHT TEST TIME ESTIMATE

The amount of time required to complete each test, based strictly on the amount of time per run and the number of runs, is calculated.

> Note: The flight test time estimates for each test are for data taking time only. Repositioning time for sequential runs, refueling and transit times are not included in each test time estimate.

Shakedown Flight Test (Test 1)

Test time: 90 minutes

- The initial system checkout will require a flexible amount of test time, estimated as 30 minutes.
- Assuming that a total of twelve runs will be required and that each run will require five minutes, this part of the test will require 60 minutes. This assumes 9 survey mode runs and 1 profiling run at area 1.1 to investigate spot densities and two runs at area 1.2.

Daytime Maximum/Minimum Detection Depth Test (Test 2)

Test time: 100 minutes

- Assuming four altitudes, three field-of-view combinations and five minutes per run, the maximum detection depth part of this test at site 2.1 will take 60 minutes.
- Assuming four altitude and two detector combinations with five minutes per run, the minimum detection depth test will require 40 minutes.

Nighttime Maximum/Minimum Detection Depth Test (Test 3)

Test time: 100 minutes

- The total time expected for Test 3 is the same as for Test 2 (Daytime Test).

Topographic and Bathymetric Vertical Uncertainty Test (Test 4)

Test time: 30 minutes

- Assuming ten passes over each of the three tests sites and allowing one minute per pass, the total test time is 30 minutes.

Horizontal Uncertainty Test (Test 5)

Test time: 40 minutes

- Assuming ten approaches to the test site from different angles, four different altitudes, and allowing one minute per pass, the test time for Test 5 is 40 minutes.

Sun Angle Test (Test 6)

Test time: 15 minutes

- Morning, midday and late afternoon runs will be conducted. Each run will take five minutes; thus a total of 15 minutes is required.

Beach Survey Demonstration (Test 7)

Test time: 135 minutes

- Assuming a test matrix of three spot diameter selections, three in-track separation distances, three altitudes, and a run time of five minutes, the beach survey demonstration will require 135 minutes.

Adding these time estimates together, one obtains a total test time of 8.5 hours. The effects of transit time can be included in an approximate way. Assuming a one way flight distance between the test site and the helicopter staging area of 25 miles, Fig. III-1 indicates that transit time will increase the flight time by 25%, to a value of 10.6 hours of flight time.

There are ground-based activities which must occur as well (see Sections V.1.1 and V.1.2). Allowing one day set up and one day to secure the HLBS for shipment, the number of test days increases to 8. Finally, the variability of weather conditions, and the important effects weather changes can produce on water clarity, may cause a significant loss of testing time. Allowing two days for these types of delays, including repeating tests due to data acquisition problems, the test plan scope is approximately two weeks.

VI.2 SCHEDULE OF FLIGHT TEST EVENTS

The following is a sequence of flight test events based on the estimates of Section VI.1, and on the assumption that the helicopter will spend about 90 minutes on station per sortie.

Note: Flight numbers indicate the test day and the sequential flight for each day, e.g. flight 2.2 is the second flight on test day 2.

Day #1

- HLBS Mobilization Demonstration
- Set up test area for Flight 2.1

Day #2

- Flight 2.1 (daytime)
  - Shakedown Flight Test
- Set up test area for Flights 3.1 and 3.2

Day #3

- Flight 3.1 (daytime)
  - Maximum Detection Depth Test
- Set up test area for Flights 4.1 and 4.2
- Flight 3.2 (nighttime)
  - Maximum Detection Depth Test

Day #4

- Flight 4.1 (daytime)
  - Minimum Detection Depth Test
  - Topographic and Bathymetric Vertical Uncertainty Test
- Set up test area for 5.1, 5.2 and 5.3
- Flight 4.2 (nighttime)
  - Minimum Detection Depth Test

Day #5

- Flight 5.1 (morning)
  - Sun Angle Test I
  - Horizontal Uncertainty Test
- Flight 5.2 (midday)
  - Sun Angle Test II
- Flight 5.3 (late afternoon)
  - Sun Angle Test III

Day #6

- Flight 6.1 (daytime)
  - Beach Survey Demonstration I

Day #7

- Flight 7.1 (daytime)
  - Beach Survey Demonstration II

Day #8

- Demobilization Demonstration

SECTION VII

LOGISTICS

This section outlines the logistical scope of the test plan based on the equipment and services described for each of the tests in section V.

VII.1 EQUIPMENT LISTING

Equipment required to perform the HLBS flight test includes:

(1) a small commercial helicopter (Bell 212 or equivalent).

(2) the HLBS system including:

- installation tools
- calibration equipment
- maintenance tools
- spare parts

(3) sufficient two-way radios for communication with land, air, and water units.

(4) emergency landing area night lighting system and power supply.

(5) miniranger microwave transponders and positioning antennas.

(6) precise survey equipment for measuring

- range
- azimuth
- elevation (leveling)

(7) equipment for measuring the seawater attenuation coefficient vs. depth.

(8) equipment for sampling the bottom composition.

(9) various markers and shapes, including,

- 2-30 meter long strings of floats
- 2-30 meter long white strips of reflective material
- 4-8 marker buoys equiped with strobe lights for night operation
- several 1-2 meter shapes for horizontal uncertainty test, either barrels or cones,

(10) data processing hardware and software including a SUN workstation (or equivalent), and graphics plotter.

(11) administrative office supplies and equipment.

SECTION VIII

TEST PERSONNEL ORGANIZATION

Successful and safe completion of the HLBS flight test depends on effective organization of the test personnel. Overall control of the flight test will be the responsibility of the flight test director. The tasking for the director will be to perform the test in a manner that collects all required data in the minimum time while maintaining safety of the planned tests as the first priority. The flight test director will be assisted by a safety officer. The responsibility of the safety officer will be to ensure safe operations at the test site.

VIII.1 PERSONNEL ORGANIZATION

The remaining test personnel can be grouped into four divisions:

- The helicopter division will consist of a flight crew and a ground crew to support helicopter operations.
- The HLBS division will consist of the ground technicians and HLBS operator(s).
- The data management division which is responsible for the collection and processing of the data acquired during the flight test, will consist of a data collection group and a quick-look analysis group. The data collection group will be tasked with the daily collection and archiving of all required data sheets, logs and tapes. The quick-look group will be tasked with producing daily data summary packages for use in planning the data collection effort.
- The test site support division will consist of the diving, boating, survey and site personnel.

Figure VIII-1 shows the organizational chart of the flight test personnel and shows the composition of each division.

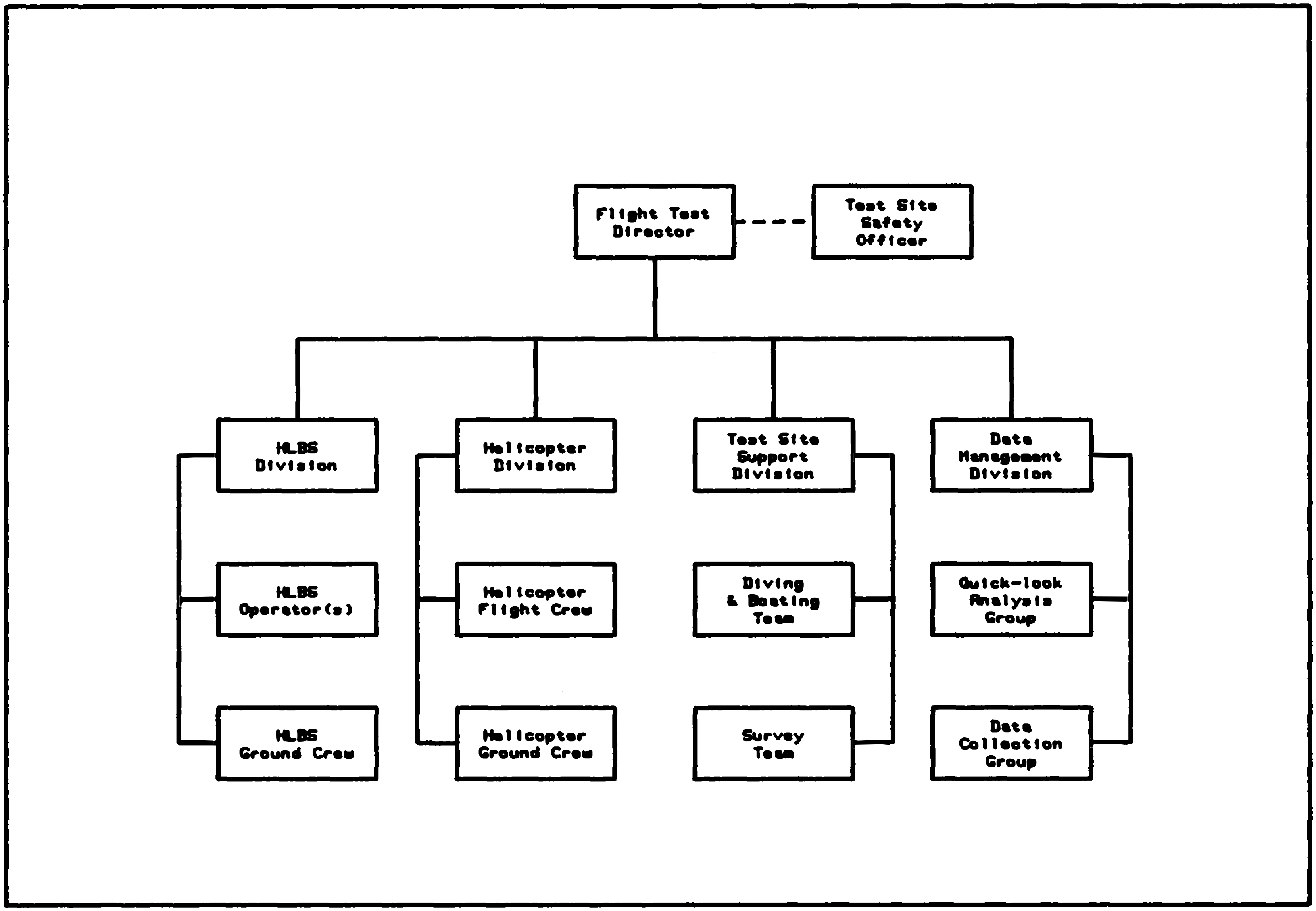

Figure VIII-1. Flight test personnel organization.

SECTION IX

DATA MANAGEMENT

The capability to effectively collect, document, distribute, process, archive and analyze data acquired in support of the HLBS flight test is essential to the success of the project. Mismanagement of data can adversely impact the analysis of experimental results. To avoid potential problems associated with data collection, special attention will be given to:

- collection of all data required to determine desired result,
- recognition and correction of data losses during testing (e.g., by malfunctioning data recorders),
- documentation of the data to permit complete reconstruction of test events, and
- data storage and retrieval procedures.

This section describes the data management actions which must be taken prior to and during the flight test.

IX.1 DATA COLLECTION

Prior to the flight test, the following actions will be taken to ensure the success of the data collection effort:

- The data requirements to support each planned test procedure will be reviewed for completeness.
- Specific data-taking responsibilities will be assigned for each test.
- Data sheets compatible with the automatic recording systems will be developed and promulgated.
- Recording equipment logs and checklists will be developed to prevent data loss during testing.
- Each participant in the flight test will be instructed in his or her data collection role.

- A data collection coordinator will be assigned to ensure the data is complete and properly documented.

IX.2 DAILY QUICK-LOOK ANALYSIS

The on-board data acquisition system of the HLBS is expected to generate approximately 540 megabytes of digital data per hour (reference a). A ground-based data processing system will be obtained and software will be developed to analyze this large quantity of data. The processing goal is a ratio of ground-based processing time to flight-time of 5:1.

With this level of processing performance, it will be possible to generate quick-look analyses of the flight test data on a daily basis. The results of the quick-look analyses will be used:

- to detect and correct any mistakes or malfunctions in the data taking process,
- to provide rapid feedback to test participants on the nature and quality of the data being taken, and
- to demonstrate the capability of the ground-based system, working in tandem with the HLBS, to produce useful bathymetric and topographic survey information.

The daily quick-look package will be the special responsibility of a group of analysts and technicians assigned to the flight test. This group will ensure that the product presents the daily results in a clear and understandable format.

IX.3 DATA PRESENTATION FORMAT

The primary objective of the post-flight data analysis is to present the results of the flight test in formats which will communicate the information to the coastal engineering and hydrographic surveying communities clearly and concisely. This requires adopting the same terminology, units of measure, reference standards and points that are used by other surveying technologies.

The formats used to present survey results should conform to certain general principles of hydrographic surveying including the following (reference f):

- The use of depth contours is recommended wherever possible.
- The survey chart must be legible, i.e. by assigning reasonable contour spacings.
- The survey chart should indicate the datum plane. If a local datum is chosen, tidal corrections will be required. If the National Geodetic Vertical Datum (NGVD) is used, a benchmark or local monument will be used to correct data.
- The scale should always be indicated on the chart.

Other data presented by the post-flight analysis group should be displayed in graphical form. The goal of each plot will be to communicate some aspect of HLBS performance in terms of the performance objectives.

SECTION X

COMMUNICATIONS

During the HLBS flight test, communications will be centralized through the test site control center. The test control center will be manned by the Flight Test Director, the Safety Officer and appropriate test site personnel.

X.1 COMMUNICATIONS GUIDANCE

The test control center will be located so that supervisory personnel can visually monitor the entire test area. The center will be in contact with all participating units during the test. Communications with the helicopter staging area will be maintained by land line if necessary.

Rules governing communication include:

- Communications which originate from the helicopter come from the pilot or copilot.
- All helicopter and boating units which participate in the exercise must be able to communicate with the control center.
- Loss of communications will require termination of the evolution in progress.
- Communications within the helicopter will be over an intercom type system. Internal communications system should provide for separate communications between pilot and HLBS operator(s) and HLBS operator(s) and onboard observers.

SECTION XI

NAVIGATION/GEOPOSITIONING

Determination of the helicopter's position is a key link in the chain of measurement which make it possible to reconstruct the position of each laser spot on the surface. This capability is essential to the success of not only the HLBS flight test, but also to all HLBS surveys.

XI.1 POSITIONING SYSTEMS

Four types of positioning systems are mentioned as candidates in reference (a) including:

- microwave
- range azimuth
- global positioning system (GPS), and
- inertial navigation.

Note: In the near term only the system making use of microwave transponders is considered feasible.

In a microwave miniranger system, at least eight transponders are deployed in a pattern which ensures that, using four channels, a fix can be obtained anywhere on the test site. In general, an external device must be mounted on the helicopter to detect the microwave signals.

The microwave miniranger system raises the following issues which must be addressed during the detailed planning for the test:

- optimal positioning of the transponders on the test site to ensure adequate coverage,
- optimal channel selection for position determination during each phase of the flight test,

- possible interference with local microwave transmissions near the test site,
- provisions for repositioning transponders in the event of casualties, and
- airworthiness of miniranger modification to HLBS aircraft.

SECTION XII

SAFETY

It is of paramount importance to conduct the HLBS flight test safely. This objective can be attained through identification of safety concerns prior to the test and with the subsequent development of procedures to minimize risk. It is necessary to designate individuals responsible for specific safety items and to define lines of communication between these individuals. As part of the overall safety effort for the flight test, contingency plans must be developed to provide an organized, prompt and correct response in event of an unusual event during the flight test. These plans should be compatible with the existing emergency response procedures of the test facility. Adequate training programs must be provided for personnel involved in the flight test.

XII.1 HELICOPTER SAFETY

Helicopter operations present inherent safety concerns. The following safety items warrant careful review prior to the flight test:

- A modification to the helicopter to incorporate the HLBS system must be finalized and air-worthiness approved.
- A modification to the helicopter to provide a mini-ranger capability must be made and air-worthiness approved.
- Accident response procedures and checklists must be in place.
- Procedures to ensure safe refueling must be promulgated.
- Emergency landing areas must be provided in advance and provisions made for night lighting.
- Ground based hazards, such as power lines, bridges and towers must be identified and helicopter flight paths adjusted accordingly.
- The proximity of aircraft traffic patterns must be established and controls provided if necessary.

XII.2 LASER SAFETY

The HLBS is designed to be eye safe to observers on the ground from all operating altitudes. Nevertheless, it must be emphasized that the coherent light emitted by a laser of the type and power used in the HLBS presents a hazard to the vision of the test participants, particularly, during testing on the ground. For this reason, stringent safety precautions must be implemented to control the emission of the laser energy including:

- personnel who use the laser and who occupy the area where the laser is in use must be aware of the hazard through training, and must be provided with eyewear,
- laser range safety must be provided,
- ground operations of the laser system must be carefully controlled and minimized, and
- detailed on-off procedures must be promulgated for the system.

XII.3 WATER SAFETY

Provisions must be made to ensure the safety of any required diving and boating operations. The philosophy of the flight test will be to minimize the number and complexity of such operations. Items which warrant review include:

- control of the helicopter and small boat traffic during such operation,
- provisions for adequate communications,
- identification and avoidance of water hazards, and
- review of local procedures for response to a diving or boating accident.

REFERENCES

(a) "Helicopter Lidar Bathymeter System Conceptual Design Report", OPTECH, Inc., OPTECH Document #DR123/1, November 1988.

(b) "Functional Specification for the Helicopter Lidar Bathymeter System", Preliminary Draft Version 2, OPTECH, Inc., May 9, 1988.

(c) "Annual Data Summary for 1983 CERC Field Research Facility", by H. C. Miller, W. E. Grogg, Jr., M. W. Leffler, C. R. Townsend, III, S. C. Wheeler, Coastal Engineering Research Center, Department of the Army, Waterways Experiment Station, Corps of Engineers,Technical Report CERC-86-9, September 1986.

(d) Aviation Week and Space Technology, Vol. 126 No. 10, March 9, 1987, p. 144.

(e) "A User's Guide to the Coastal Engineering Research Center's (CERC's) Field Research Facility", W. A. Birkemeier, H. C. Miller, S. D. Wilhelm, A. E. DeWall, C. S. Gorbics, Introduction Report CERC-85-1, May 1985.

(f) "Surveying and Charting of the Seas", W. Langevaar, Elsevier Oceanographic Series, Vol. 37, Amsterdam, 1984.

APPENDIX A

A PRELIMINARY SITE ANALYSIS OF THE CERC FIELD RESEARCH FACILITY AT DUCK, NORTH CAROLINA

This Appendix gives a brief description of the research facility at Duck, North Carolina, and evaluates this site as a potential HLBS test site. Section A.2 discusses the environmental conditions which would impact the flight test. Section A.3 describes the logistical support and Section A.4 discusses the ground-truth survey capabilities at this site. Section A.5 present conclusions. Section A.6 discusses areas requiring further investigation.

This Appendix is based on information (references (c) and (e)) provided by Mr. W. A. Birkemeier, Field Research Facility. His assistance was very helpful and greatly appreciated.

A.1 SITE DESCRIPTION

The U.S. Army Corps of Engineers, Waterways Experiment Station, Coastal Engineering Research Center (CERC), Field Research Facility (FRF) at Duck, North Carolina, is a 176 acre facility located near the middle of Currituck Spit, near Kitty Hawk, North Carolina. The FRF is bordered to the east by the Atlantic Ocean and to the west by Currituck Sound.

The facility consists of a 561 meter long research pier, an office and field support buildings. The research pier provides a rigid platform from which oceanographic and meteorologic measurements can be made throughout the year.

A.2 ENVIRONMENTAL CONDITIONS

This discussion of environmental factors at the FRF will follow the organization of Section III.1, by presenting the seasonally independent factors first. All data reported here was obtained from reference (c).

Bottom topography. The near shore (up to one kilometer seaward) bathymetry at the FRF is characterized by:

- a moderately sloping bottom,
- an outer storm bar at a depth of 4.5 meters,
- an inner bar at depths between 1 and 2 meters,
- a trough beneath the research pier, and
- a scour hole, three meters deeper than the adjacent bottom, at the seaward end of the pier.

Figure A-1, reproduced from reference (c), is a contour diagram illustrating the bottom topography of the FRF site.

This bottom profile satisfies the basic requirements of the HLBS flight test in the following areas. The flight test requires a flat region of detectable depth to determine the depth uncertainty independent from position uncertainty (See Section V.3.4). Such a region is the one marked "A" in Figure A-1, which is constant to within 0.5 meters. The maximum detection depth test is best performed on a gently sloping bottom such as that found near the region marked "B" on Figure A-1. Bottom irregularities are also present at the FRF. These include the sand bars, the trough and scour hole near the pier, and the pier pilings, marked "C" on Figure A-1.

The only flight test requirement which may present difficulties is the minimum detection depth test, which must be performed at depths of 1 to 2 meters. These depths occur at the point marked "D" on Figure A-1. Unfortunately, this region may be in the surf zone, where the associated foam and spray of wave action will scatter the laser light

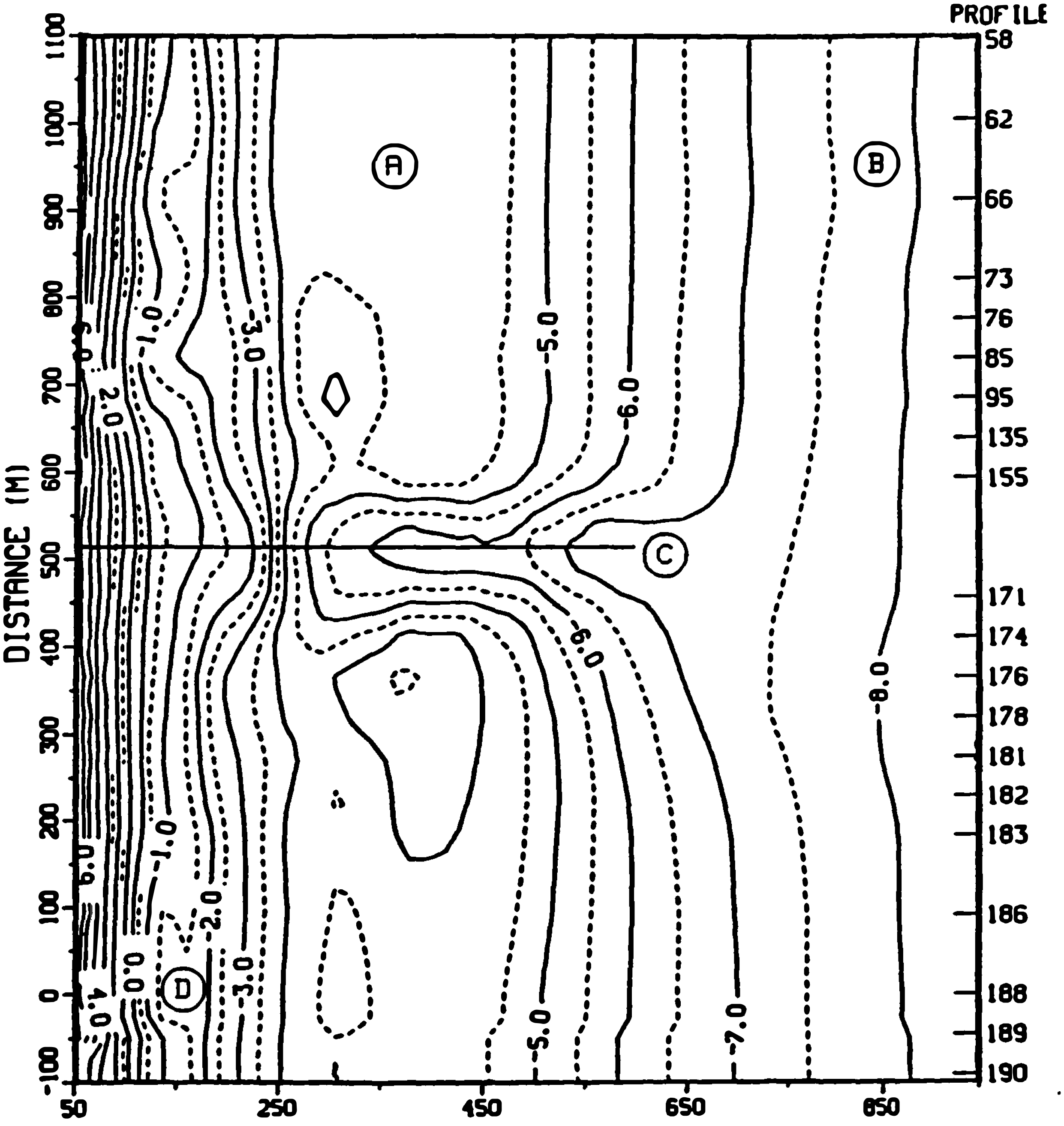

Figure A-1. FRF bathymetry, 12 July 1983 (contours in meters)
(reproduced from reference c)

very effectively. An alternative test site for the minimum detection depth test may be available on the western side of the FRF, on Currituck Sound.

Bottom Type. The sediments at FRF have the following characteristics:

- The sediments on the beach front and beach step consist of a mixture of coarse 1-2mm gravel mixed with fine to moderate sand.
- Offshore sediments are well sorted with sand size decreasing with distance from shore.

A sand or gravel bottom of the type described above should present a well defined, reflective optical boundary. Thus, the bottom at FRF appears to satisfy the flight test requirements.

The environmental factors which are seasonally dependent; including weather conditions, water clarity and wave height, are discussed below.

Weather conditions. Weather conditions that could impact helicopter operations during the HLBS flight test include fog, precipitation, and wind. Precipitation at FRF is distributed evenly throughout the year. In winter, this precipitation is caused by mid-latitude cyclones (low pressure systems): in summer, most precipitation is the result of thunderstorms. Winds are generally higher in the fall and winter months. For example, it is common for wind speeds to average in excess of 15m/sec during winter storms. No data was available in reference (c) on the frequency of low visibility conditions.

Water clarity. Water clarity is measured at FRF using the Secchi disc method. This data can be converted into the attenuation coefficient K by using the formula

$$K = \frac{1.6}{Z_S} \qquad \text{(A-1)}$$

where Z_S is the Secchi depth measured in meters.

Using equation (A-1), the seasonal visibility data in reference (c) can be converted into a seasonal plot of K. The K data collected in 1980-1982 is displayed in Figure A-2. It is desirable that the maximum detection depth of the HLBS be tested up to a depth given by $Kz = 4$. Figure A-3 shows the depth z which meets this test requirement as a function of the time of year. From this plot, it appears that the deepest depths can be sounded at FRF during the summer months, particularly, June or July. During the summer months, the full survey area shown in Figure A-1 is likely to be available for survey by the HLBS.

It should be noted that even in the summer months, the water clarity tends to follow the prevailing winds. When easterly winds prevail, the water clarity decreases as cold, murky water is brought to the surface. Westerly winds move warm, clear water towards shore and visibility improves. This variability in water clarity may make flight tests impractical on certain days. Additional time is provided in the recommended flight test schedule to accommodate these potential delays (See Section VI).

Wave height. Figure A-4 shows the seasonal dependence of the mean wave height. Comparing Figure A-4 to Figure A-2, the wave height shows the same seasonal dependence as the attenuation coefficient, K. More significantly, extreme wave heights are minimal in the summer months, declining from a maximum of 3.8 m in February to a minimum of 1.0 m in July. Once again, the data indicate that it is desirable to conduct the HLBS flight test at the FRF in the summer, preferably, in June or July.

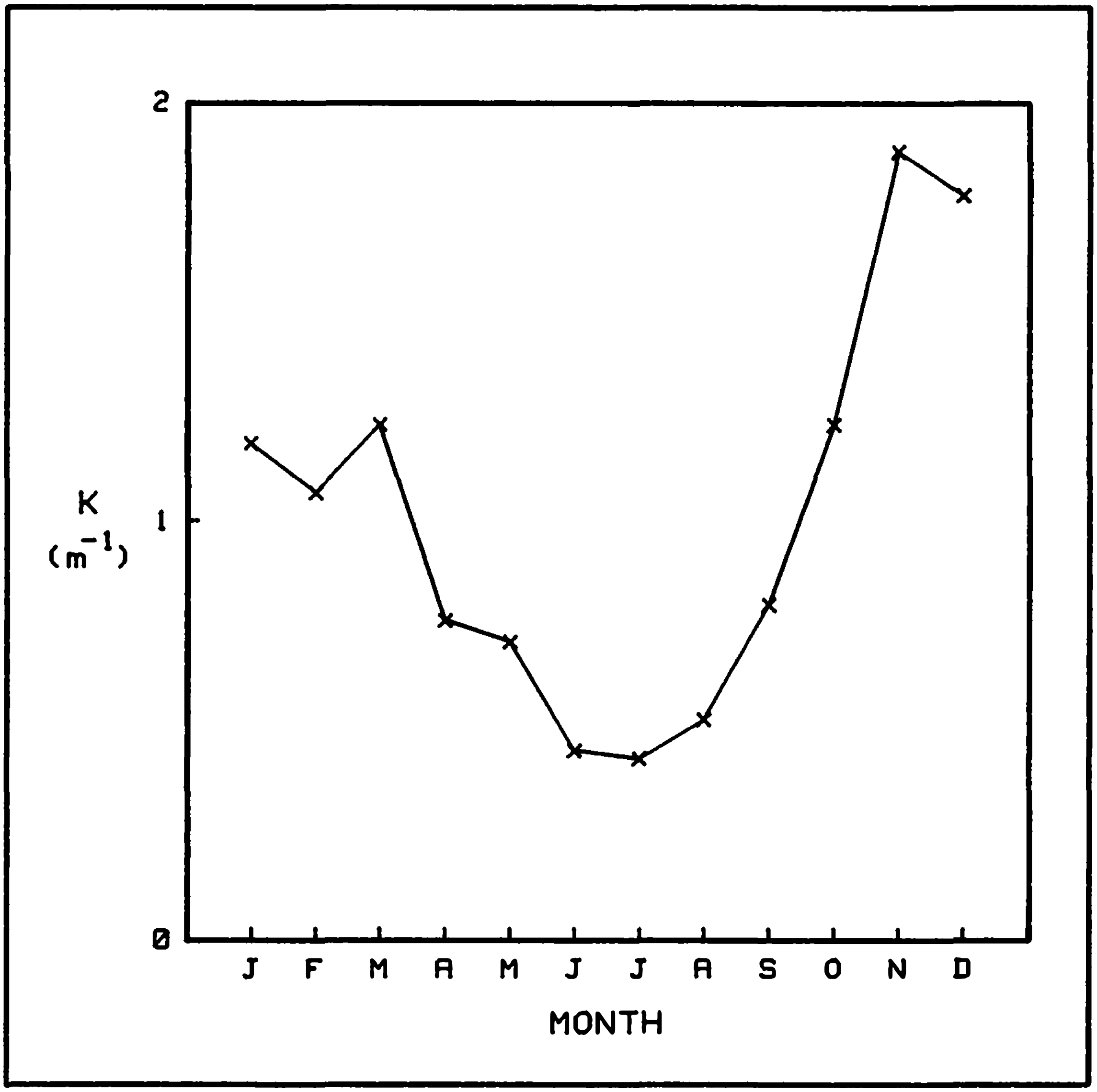

Figure A-2. Seasonal dependence of the monthly mean attenuation coefficient, K, at FRF (1980-82). (Data derived from reference c)

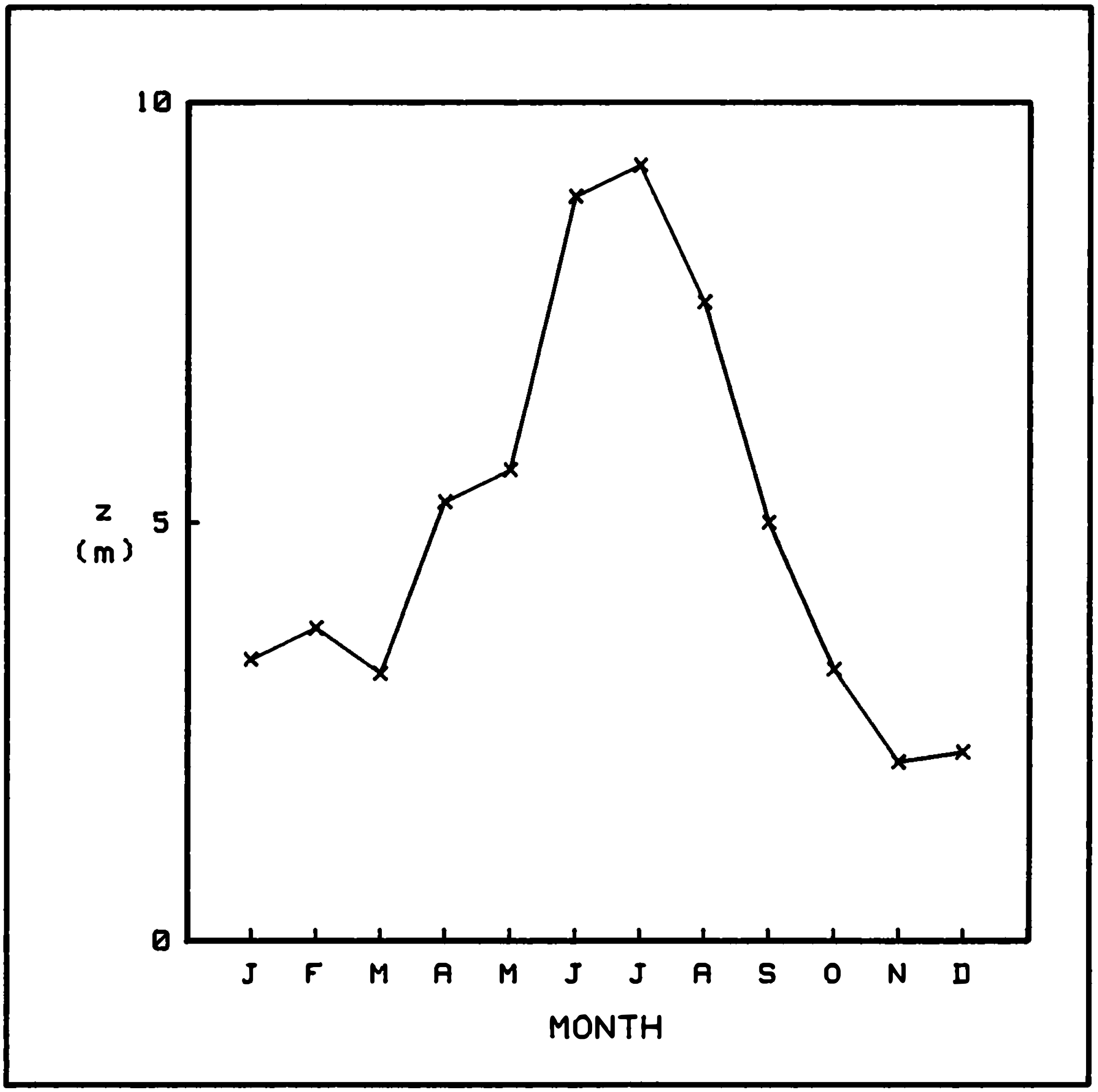

Figure A-3. Predicted seasonal dependence of the HLBS maximum detection depth, z, based on Kz = 4.

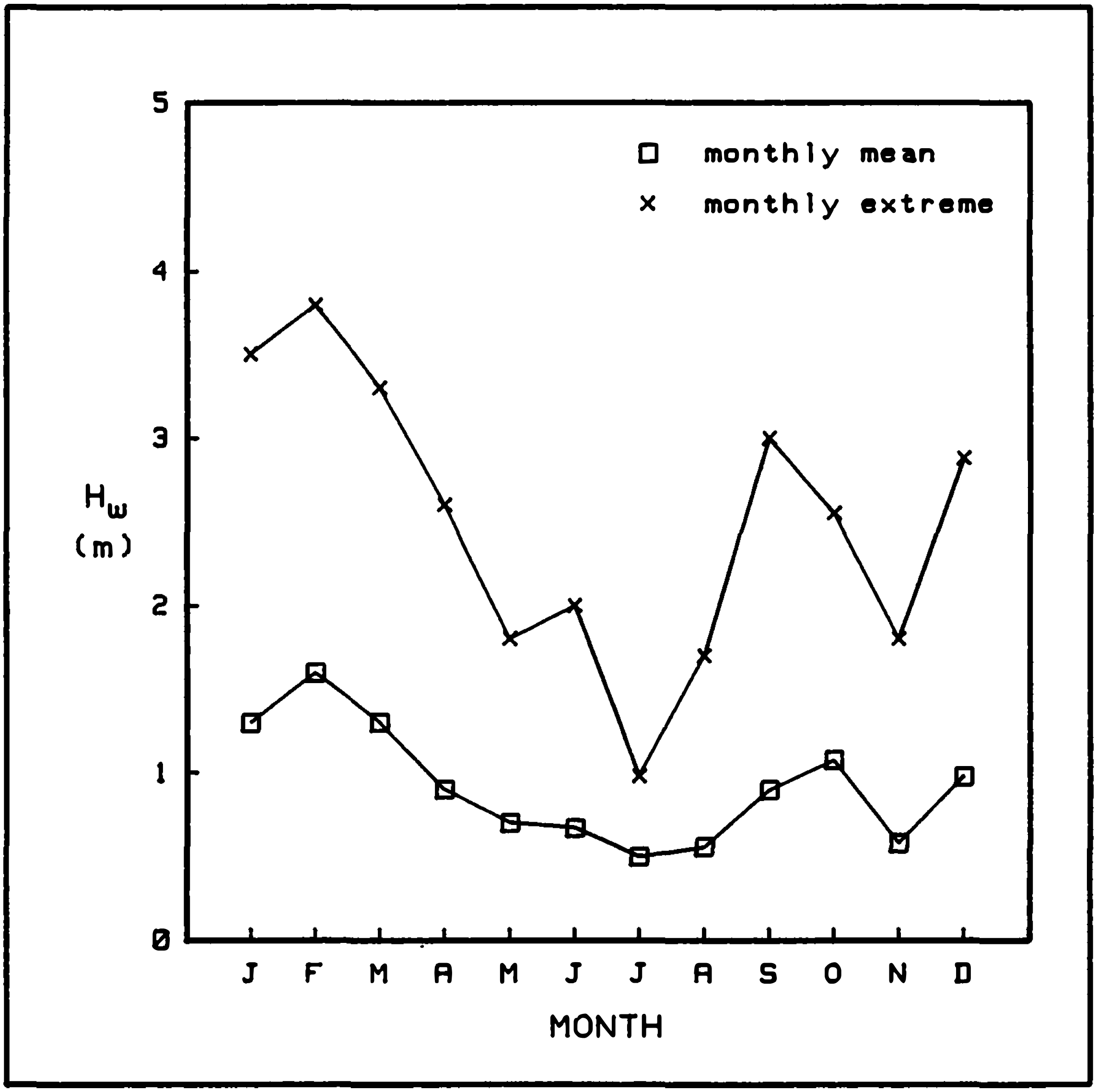

Figure A-4. Seasonal variation of monthly mean and extreme wave heights at FRF (1983).
(reproduced from reference c)

A.3 LOGISTICAL SUPPORT

The logistical support capabilities associated with the FRF at Duck, North Carolina and the surrounding area are summarized in this section. An in-depth discussion of these issues is presented in reference (e).

The logistical support of the helicopter is a primary concern. Two types of landing facilities are available near the FRF: areas at which the helicopter could set down temporarily to transfer equipment and personnel or to respond to an emergency, and areas at which the helicopter could be refueled or maintained.

Landing areas near the FRF with no services available include:

- the access road to the FRF,
- the FRF parking area,
- a flat area located on the FRF compound which is grass covered, and
- First Flight Airstrip, a landing strip at Kill Devil Hills, North Carolina, approximately 15 miles away.

In an emergency, the beach, which extends uninterrupted along the western edge of the test site, could be used as a landing site.

Staging sites for the helicopter include:

- Manteo Airport at Manteo, North Carolina, approximately 25 miles away. Facilities include aviation gas, keyed lighting for night flights, and automatic direction finder (ADF) approach.
- Coast Guard Facility at Elizabeth City, North Carolina, also about 25 miles away.

A twenty-five mile transit flight will increase the length of the test. Referring to Figure III-1, the number of flight days per flight test hour would increase approximately twenty-five percent for the Bell 212 helicopter. It is reasonable to assume that the flight test length would be increased by a similar proportion.

Other logistical issues related to the FRF which are of importance to the flight test are the following:

Travel. Air travel to and from the region can be routed through Norfolk International Airport in Norfolk, Virginia, located approximately 85 miles away by car. Alternatively, commuter airline service is available between Norfolk and Manteo Airport.

Car rental. Rental cars are available at Norfolk Airport, Manteo Airport and are seasonally available between 15 May and 15 November at First Flight Airstrip.

Office space. The FRF laboratory building contains offices, a kitchen, a library, a computer room, a multi-purpose area, and a diving locker. The computer room contains a Digital Equipment VAX-11/750 and a WICAT 150 microcomputer. It is possible that arrangements could be made to share these facilities with the FRF staff on a limited basis. There is also a 15m x 3m trailer with electricity, heat and air conditioning (no water) available to visiting scientists. There are also numerous rental properties in the area which could be used to provide adequate office space during the flight test.

Equipment storage. There is limited space available at the FRF to store flight test equipment.

Electricity/telephones. In addition to normal electrical and telephone service, the FRF has an emergency generator combined with a Westinghouse uninterrupted power supply to support data collection equipment.

Observation platform. The roof of the laboratory building provides a flat observation deck with an elevation of 12.6 meters above vertical datum.

Lodging. There are twenty motels and numerous rental properties within sixteen miles of the FRF.

A.4 GROUND-TRUTH SURVEY CAPABILITITES

The FRF possesses an impressive oceanographic data collection and bathymetric survey capability. This section details the capabilities and relates them to the ground-truth requirements for the HLBS flight test.

Bathymetric ground-truth. Bottom profiles are obtained periodically by a 10.7 meter tall amphibious tripod device, the Coastal Research Amphibious Buggy (CRAB). The x,y position of the CRAB is determined by a ground-based surveying system. Reference (c) states an accuracy of ±3 cm for horizontal and depth measurements made by the CRAB. The survey area mapped out by the CRAB extends approximately one kilometer seaward and 0.6 kilometers to the north and south of the pier. Additional soundings are taken along the pier, using a weighted tape. The ten meter depth limitation of the FRF survey technique does not appear critical in view of the maximum bottom detection depths predicted for the area (Figure A-3).

Water attenuation coefficient. The FRF currently maintains the capability to measure the water visibility by means of a Secchi disc measurement, taken daily at the seaward end of the pier. Because the flight test requires the depth dependent K to be measured at various locations, this capability will have to be augmented.

Meteorologic/oceanographic data. The extensive set of oceanographic and meteorologic data collected by the FRF on a continuing basis will be useful in interpreting the flight test results.

Bottom samples. Bottom samples and visibility measurements can be made with an amphibious craft at FRF called the LARC-V (reference e).

A.5 CONCLUSIONS

- The near shore bottom topography, bottom depth and bottom type meet the flight test requirements.
- The foam line caused by surf action may interfere with the minimum detection depth determination. An alternate site must be identified as detailed test planning progresses.
- The climatic, visibility, and wave height conditions at FRF indicate that the optimum period for conducting a flight test at Duck, North Carolina is in June or July.
- The ground-truth bathymetry of the FRF site surpasses the requirements for the HLBS flight test.
- The capability of the FRF to measure the sea water attenuation coefficient will have to be augmented for the flight test.
- Careful attention must be given to helicopter and other logistical concerns during the detailed test planning to ensure that problems presented by the remote location of the FRF are properly addressed.
- Based on the outstanding support available and the favorable conditions during summer months, it is recommended that the HLBS flight test be conducted at Duck, North Carolina.

A-6 AREAS FOR FURTHER INVESTIGATION

The following areas should be addressed as specific plans for use of the FRF as a flight test site are developed:

- The capabilities of the two potential helicopter staging areas must be detailed and compared.
- An alternative site for the minimum depth detection test must be identified.
- Techniques for measuring the attenuation coefficient profile of sea water should be identified.
- The variability of the sea water attenuation coefficient near the FRF should be investigated further.