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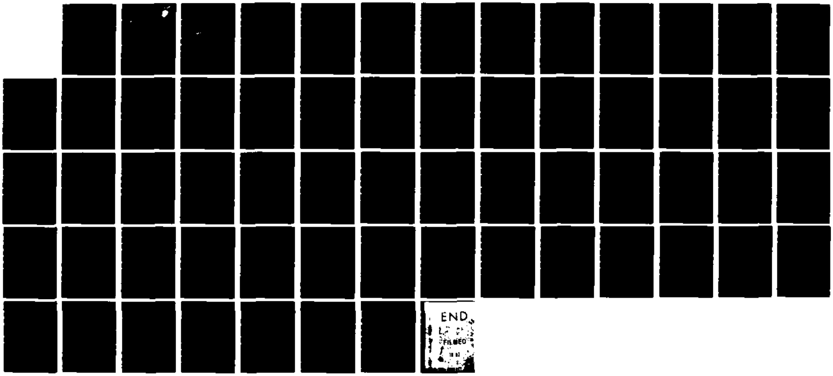

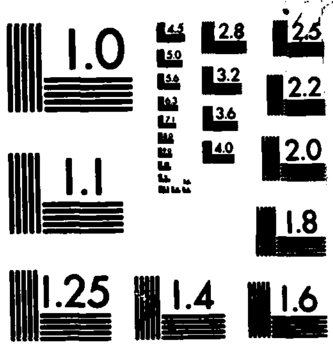

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RADC-TR-83-60
Final Technical Report
March 1983

MULTISPECTRAL DATA PROCESSING SYSTEM

W. W. Gaertner Research, Inc.

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
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This report summarizes the research performed in the design and specification of the computer system architecture and sortware required for the Multispectral Data Processing System (MDPS). The objective of the MDPS is the efficient processing of large volumes of digital bathymetric data (collected by remote multispectral sensor) representing depths and bottom features of shallow water coastal areas, navigable channels and bays, and offshore shallow reefs. The MDPS includes the data recording and pro-

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cessing portions of an airborne active/passive bathymetric system which can be used by the Defense Mapping Agency for the production and maintenance of navigation charts. Also discussed are

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TABLE OF CONTENTS

1. INTRODUCTION

1.1 General

This is the Final Report on Contract No. F30602-81-C-0035, "Multispectral Data Processing System (MDPS)".

The MDPS is the data recording and processing portion of an airborne active/passive bathymetric system which the Defense Mapping Agency plans to implement for the collection and charting of depth and bottom-topography information for coastal waters. Under the terms of the contract, which was administered and monitored by the Rome Air Development Center, the contractor, W. W. Gaertner Research, Inc., has conducted a study to specify and design the MDPS computer architecture and software for the efficient recording and processing of the large volumes of data required by the system. The original Statement of Work for the study imposed no conditions as to where and when the processing should be performed. However, after evaluating the initial part of the study, the Requirements Analysis, the sponsors and contractor concluded that the system should be divided into two parts as follows:

Airborne Processing and Recording System: Controls airborne data collection, records data on high-speed digital magnetic tape, and performs limited computations to enable operator to monitor system performance in the air.

Ground Processing System: Performs post-flight processing of recorded data to generate depth at observed points. Through resampling process, assigns depths to points on a pre-determined geographic grid.

This functional separation between air and ground was effected in the subsequent stages of the study, which covered the system architecture and specifications.

1.2 Interim Technical Reports

In the course of the MDPS study, the contractor, in conformance with the CDRL, wrote and submitted three Interim Technical Reports in four volumes. Ten copies of each report were submitted to RADC/ISCA. The reports are listed below:

Item No. A002, Technical Report (Interim), Requirements Analysis, 1 December, 1981.

Item No. A003, Technical Report (Interim), Systems Architecture, 10 August, 1982.

Item No. A004, Technical Report (Interim), Specifications, Vol. I: Ground Processing System, 10 December, 1982.

Item No. A004, Technical Report (Interim), Specifications, Vol. II: Airborne Processing and Recording System, 23 December, 1982.

These reports, which total more than 600 pages, contain the primary technical detail of the study and should be referred to if such details are required. The contents of the four Interim Report volumes are listed in an Appendix to this Final Report.

It must be recognized that the Interim Reports were written in the course of an evolving study which extended over approximately two years and involved numerous reviews and consultations with the sponsors and other experts. Therefore, while the basic system concepts are totally consistent, some algorithms and procedures are changed and some new ones are added from report to report. Each such change or addition is noted and justified at the point at which it is introduced.

1.3 Organization of Report

As discussed in Chapter 1.2, this Final Report constitutes a project summary, with readers referred to the Interim Reports for technical details. Therefore, Chapters 2 and 3 summarize the conclusions at the system, and hardware and software levels, respectively. Chapters 4 and 5 present new material. Chapter 4 contains the cost analysis required by the contract. Chapter 5 presents some results of a preliminary error analysis.

2. SYSTEM

2.1 Basic Theory

The theoretical basis of the depth measurement technique to be used in the proposed bathymetric system is a mathematical model relating depth at any given point to the signal received from that point by a passive scanner tuned to a particular frequency. The equation for the model can be written as

$$V_i = V_{si} + V_{oi}e^{-2K_iZ} \quad . \qquad (1)$$

The subscript "i" denotes the frequency, i.e., it indicates that the factors having this subscript will depend on the particular frequency at which the scanner measurements are taken.

The meanings of the terms in equation (1) are as follows:

V_i is the total signal detected by the scanner (at frequency i) at the point of measurement, or more precisely, over a small area (pixel) centered at the point of measurement.

V_{si} is that portion of V_i which results from effects other than the reflection of light from the bottom. Primarily it is due to upwelling light from the water mass itself (i.e., light reflected from matter in the water), surface reflections, and sun glint. It is sometimes called the "deep water" term, since it is present even when, owing to the depth of the water, there is no bottom reflection.

V_{oi} is the signal component which would result from light reflected from the (wet) bottom if there were no attenuation due to the water, i.e., at zero depth. For a given ambient light condition, V_{oi} will depend on the bottom reflectance, which in turn will depend on the bottom type (material) within each particular pixel.

K_i is the attenuation (per unit distance) of the light as it passes through the water. For a given i, K_i will depend on the water type. The factor 2 accounts for the total path of the light through the water, from the surface to the bottom and back to the surface.

Z is the water column length, defined as the path length of the refracted light from the surface of the water to the bottom. Z is related to the water depth by a geometric conversion factor which is a function of the angle between the vertical and the line-of-sight to the pixel at which the measurement is made. Since this angle is known, it is a simple matter to determine depth from Z.

If we subtract V_{si} from both sides of equation (1) and then take the natural logarithm (ln), we have the equation

$$\ln(V_i - V_{si}) = \ln V_{oi} - 2K_iZ \quad . \tag{2}$$

We can see from this equation that if V_{si}, V_{oi}, and K_i are known, we can determine Z by measuring V_i.

For limited survey times and areas (to be discussed in subsequent paragraphs), V_{si} and K_i can be considered constant and the variation in V_{oi} can be largely compensated for. Thus, the basic procedure on which the active/passive bathymetric system is based is as follows:

First, a small set of passive measurements is made and from these measurements V_{si} is computed. We have called this Phase I.

Second, a small set of simultaneous active and passive measurements is made. From these measurements, and the values of V_{si} computed in Phase I, coefficients are calculated which are related to V_{oi} and K_i. This we call Phase II.

Third, values of V_i are measured passively (i.e., by the scanner only) at a large number of points. At each point, the measured value is combined with the coefficients determined in the prior phases to calculate the water column length, Z, and the depth. We have called this Phase III.

2.2 Deep Water Phase

When the water is deep enough so that there is no bottom reflection, the signal measured by the scanner is due entirely to V_{si}. Thus, we can determine V_{si} by flying for a short time over deep water and taking scanner measurements. In order to eliminate the effects of scanner or other random noise, we average the measurements over a number of scans. At a scan rate of 60 per second, we can collect and average 1000 scans in less than 17 sec. of flight.

The scanner collects data simultaneously at all scan angles within its total angular range. Since V_{si} can vary with the scan angle, we use all of the data, computing a separate average for each angle. We must also, of course, determine separate averages for each value of i. If sun glint is present, it will also affect the value of V_{si}. To determine the presence of sun glint, measurements are made in a near infra-red band and these are correlated with the visible band measurements. A high correlation indicates that sun glint is present and a correction term is computed.

For each scan angle, V_{si} will remain essentially constant as long as the ambient light conditions remain constant, although there may be some variation with water type and sea state. Thus, the range of utility of a given set of V_{si} is largely a matter of time. If sun elevation, cloud cover, or atmospheric transmittance change significantly during the flight, a new set of deep water measurements will have to be taken and averaged.

2.3 Active/Passive Phase

To obtain the other two coefficients, V_{oi} and K_i, we take simultaneous active and passive readings over a relatively small set of points. The active readings are taken with the laser depth measurement system, the passive with the scanner. The actual coefficients which are calculated are not V_{oi} and K_i themselves but two related functions.

The procedure has its basis in equation (2). Solving that equation for Z,

$$Z = (1/2K_i) \ln V_{oi} - (1/2K_i) \ln (V_i - V_{si}) \; . \tag{3}$$

Since V_i is measured at each observed point and V_{si} has already been determined, we can determine $\ln (V_i - V_{si})$. We introduce the notation

$$X_i = \ln (V_i - V_{si}) \tag{4}$$

so that (3) becomes

$$Z = (1/2K_i) \ln V_{oi} - (1/2K_i) X_i . \tag{5}$$

Let

$$B_o = (1/2K_i) \ln V_{oi}$$

$$B_i = (1/2K_i) \tag{6}$$

Then

$$Z = B_o + B_i X_i \tag{7}$$

Let us make the tentative assumption that B_o and B_i are constants. Then we can estimate values for these constants by linear regression.

That is, we determine the values of B_0 and B_i which minimize the sum of the squares of the difference between the value of Z given by equation (7) at each point and the value measured by the laser at the same point. These estimated values, the "regression coefficients", are denoted by b_0 and b_i.

Assuming the errors in the laser and scanner data are unbiased (i.e., have mean zero), b_0 and b_i will be good estimates for B_0 and B_i if the number of active/passive points used in the computations is sufficiently large. An error analysis has shown that, for a representative example, a set of between 200 and 400 points should be sufficient. Thus even at an observation rate of only 20 per second (the minimum laser pulse repetition rate) an adequate set of regression values can be obtained from only a few seconds of data.

Now we must examine the assumption that B_0 and B_i are constants. Equation (6) shows that B_i depends only on the attentuation coefficient, K_i, and thus only on the water type. This can be assumed to be constant if the area over which a given set of regression coefficients is computed and used is kept small (i.e., if we divide the survey area into many small parts and compute a different set of regression coeffients for each). Since, as discussed above, data for a set of coefficients can be obtained in only a few seconds of flight, this will not be a problem. Thus, it can be assumed that B_i is truly constant.

B_0 is another matter. As can be seen, it depends not only on K_i but also on V_{0i} and therefore on the bottom type. There is no general way to restrict the active/passive observations to a single bottom type, since the bottom composition may change every few feet. However, the reflectance of any given bottom type depends on the frequency of the light being reflected. Owing to this fact, the effect of bottom type variations may be greatly reduced, in some cases even eliminated, by using passive observations at several different frequencies.

In the second Interim Technical Report (Item No. A003) we have shown that if the number of passive frequencies used is equal to the number of bottom types in the scene (area over which the regression coefficients are calculated), there will be a unique linear combination of the signals in these frequencies which will produce the correct value of Z at any point in the scene, no matter which of the bottom types is present at that point. Thus, for example, if there are three frequencies, denoted 1,2,3, and three bottom types, there will exist a set of coefficients, B_o, B_i, B_2, B_3, such that an extended form of equation (7),

$$Z = B_o + B_1X_1 + B_2X_2 + B_3X_3 \tag{8}$$

will give a correct value of water column length over all 3 bottom types. As in the single-band case, the coefficients can be estimated by regression, using the laser depth together with the passive signals in all three bands. The regression coefficients are denoted b_o, b_1, b_2, b_3.

If the number of bottom types is greater than the number of frequencies used, complete cancellation of the bottom effects will not be possible. However, since, as was discussed above, a particular set of regression coefficients need be applied over only a small area, it is reasonable to expect that in most cases each regression area will encompass only a small number (say, 3 or 4) of bottom types or that, at least, the bottom types will group into a small number of sets, with only minor reflectance variations within a set, which will result only in acceptably small depth errors.

If the number of bottom types is less than the number of frequencies, the regression process will not lead to a solution. This condition can be detected by a test on the data and the number of frequencies reduced.

It has been assumed in the study that the scanner will be able to make measurements in 4 visible-light frequencies at any one point, but that only three of these frequencies (eliminating the noisiest) will be used in any one regression area. However, noise levels permitting, there is no reason why all 4 frequencies could not be used if there are 4 or more distinct bottom types in the scene.

2.4 Laser Depth Calculations

The laser depth, required in the active/passive phase, is determined from the time interval between two peaks in the laser return, the first (earliest) peak representing the return from the surface and the other the return from the bottom. These peaks are found by examination of the digitized laser return. However, it is not sufficient merely to detect two isolated maxima. Noise may make the maxima indistinct or produce isolated spikes. Thus, it is necessary to find each peak by fitting a curve to all of the data in the peak vicinity. The maximum point of this fitted curve will be considered the peak of the particular return.

The proposed procedure is first to detect the approximate position of a peak and then to correlate the data in the vicinity of that position with one or more pre-stored waveform "templates". For a given template, the position yielding the maximum correlation is determined, and the template peak in that position is taken to be the return pulse peak. Since it is not known to what extent the shape of the return pulse will be affected by environmental conditions, provision has been made to store several templates. The template yielding the highest maximum correlation is deemed to represent the actual return pulse configuration and position of the maximum is deemed to represent the position of the pulse.

Although in the initial system configuration the laser pulse repetition rate may be only about 20 per second, the system has been specified to carry out the multi-template correlation process for up to 100 pulses per second, to allow for future improvements.

2.5 Passive Phase

Once the V_{si} and the correlation coefficients have been determined, depths can be calculated from passive observations only. This makes it possible to obtain a large number of depths from data collected in a short period of time. The scanner is assumed to cover a 90° angle (45° on each side of the nadir) with an element resolution of 2 milliradians. Thus, a full scan will comprise 785 pixels. Some pixels at the ends of the scan line may be lost due to aircraft roll, but it is reasonable to assume there will be at least 700 pixels in an average scan. At 60 scans per second, this provides about 150 million depth observations in one hour of passive flight. Even if this hour is preceded by an hour spent collecting active/passive data to be used in generating sets of correlation coefficients, the average over the entire flight will be 75 million depth points per hour. To achieve this with a purely active system would require a laser operated at over 20,000 pulses per second.

Let X_{i1u} denote the passive reading, X_i, as defined by equation (4), for pixel u of scan line 1. Let L_{1u} be the water column length for this pixel and scan calculated from the passive readings and the regression coefficients. Then by analogy with equation (8),

$$L_{1u} = b_o + b_1X_{11u} + b_2X_{21u} + b_3X_{31u} , \tag{9}$$

assuming the use of 3 bands.

If the pixel number, u, has been properly offset for the roll of the aircraft, the factor for converting from water column length to depth will depend only on u and therefore can be stored as a table in the computer memory.

Finally, it will be necessary to determine the geographic position of each pixel at which depth has been measured. To make this possible, the aircraft must carry a position and attitude measurement system. It has been assumed in the study that this will be a combination of a navigation satellite receiver for position fixes and an inertial navigation system for attitude measurement and extrapolation between fixes. A precise altimeter must also be provided.

2.6 System Parameters

The MDPS design has been based on a number of assumptions regarding functional parameters of the active/passive bathymetric system. These parameters are listed below. Most of them were either given at the outset of the project or established by discussion with the sponsors.

Passive Scan Rate:	60 per second
Total Angle of Scan:	90°
Angular Scan per pixel:	2 milliradians
Number of pixels per scan (at 0 roll):	785
Number of visible bands per scan:	4
Number of IR bands per scan:	1 or 2
Maximum altitude during passive scan:	15,000 ft.
Laser pulse repetition rate:	20 to 100 pulses per second
Altitude during laser readings:	500 to 2,000 ft.
Maximum survey time (on station):	3 hours
Positional accuracy of aircraft:	15 meters RMS
Maximum measured depth:	30 meters
Depth accuracy (RMS):	0.3 meters for depths less than 20 meters 1.0 meter for depths greater than 20 meters.

2.7 Flight Scenarios

In order to determine the data handling and processing requirements, it has been necessary to make certain assumptions regarding the sequence of data collection. For this reason, two general flight scenarios have been considered.

In Scenario #1, data collection Phases II and III (i.e., active/passive and pure passive) take place simultaneously. In processing, the data must be separated so that for a given zone the regression coefficients are calculated first and then applied to the passive readings to obtain the depths as discussed in Chapter 2.5. This requires the use of a variable delay, to be implemented in the Ground Processing System by means of a disk. In this scenario, the entire flight must take place at altitudes compatible with laser depth measurement, i.e., under 2,000 ft.

In Scenario #2, data for Phases II and III are collected separately. The aircraft first flies over the survey area, or a sector thereof, making laser readings and taking passive data at the laser points only. It then retraverses the area collecting purely passive data for entire scans. With this scenario, the data required for regression coefficient calculation automatically precedes the passive data to which the regression coefficients are applied, and no data separation and delay is required. Clearly, Scenario #2 is the more costly in flight time, since it requires that the aircraft pass over a given area twice. However, this is more than made up for by the fact that the passive-only data can be taken at much higher altitudes than the active/passive, since it is not limited by the maximum laser altitude. Since the linear width of the scan is proportional to the altitude of the aircraft, Scenario #2 can produce total scan widths an order of magnitude greater than those of Scenario #1. In addition, the aircraft should be able to operate at higher speeds at higher altitudes, and therefore to produce more coverage in the forward direction as well. Taking all of these factors into account, Scenario #2 should produce 4 to 10 times the area coverage of Scenario #1, for the same on-station flight time.

2.8 Interim Technical Report References

The following list references chapters or appendices of the Interim Technical Reports where more detailed information can be found regarding the topics discussed in the preceding chapters. The reports are designated by their CDRL item numbers, i.e., the First Report is A002, the Second Report is A003, the Third Report, First Volume, is A004-I, and the Third Report, Second Volume, is A004-II. As mentioned earlier, some details given in the earlier references may have changed as the project progressed; in their essentials the referenced chapters represent the project results.

Deep Water Term Equations	A003	Ch. 4.2
Deep Water Term Computations	A003	Ch. 5.3.2.1
Regression Computations	A002	App. C
Laser Depth Calculation	A003	Ch. 4.3
Depth Calculation	A002	Ch. 6.2 (geometric correction)
Bottom-Type Variations	A003	Ch. 4.5
Regression Coefficient Selection	A003	Ch. 4.6
Choice of number of bands	A004-I	Ch. 2.2
Flight Scenarios	A003	Ch. 3.3
Data Rates	A003	Ch. 5.2.1
Navigation and Attitude System	A002	Ch. 5.4

The proposed resampling procedure, for assigning the depths to a geographic grid, is first discussed in A003 Ch. 4.4. In that place, it is associated with a particular interpolation algorithm. In the subsequent report, A004-I Ch. 2.2, the identical resampling procedure is presented but in association with an improved interpolation scheme. After further discussion with the sponsors, it appears that it may be desirable in some applications to use a nearest neighbor assignment procedure with no numerical interpolation. This is easily accomplished by a simple modification of the procedure described in the last paragraph of A004 Ch. 2.2. First, the linearization is performed using a table of nearest neighbors rather than interpolation factors. Each of the linearly-spaced pixels is assigned the depth value of the nearest neighbor "raw" pixel, as determined from the table. Then further interpolations both along and between scan lines are also performed on a nearest neighbor basis. An even number of interpolated points should always be used so there will be no ambiguous case of a point half way between two neighbors. The resampling scheme then procedes as proposed in the Interim Technical Reports, by calculating the North and East coordinates of each point and rounding each coordinate off to the nearest grid value. However, in this case when two or more depths are assigned to the same grid point, we will use the smallest, thus insuring that coral heads or other projections which might constitute navigational hazards will not be missed. It should be noted that this procedure will require less computation than the interpolation procedure described in A004, and therefore will not introduce any computer throughput problems.

As noted in Chapter 1.3, Appendix A lists the complete contents of all of the Interim Technical Reports.

3. HARDWARE AND SOFTWARE REQUIREMENTS

3.1 General Considerations

Although operationally the airborne system is used first, discussion of the MDPS hardware and software requirements is best approached by first considering the Ground Processing System. The reason for this is that the airborne computations are, to a large extent, a subset of the ground computations, and therefore will be discussed most easily if the ground requirements are covered first. This is the sequence which has been followed in the Third Interim Report (Item No. A004), which presents the specifications, and will be used in the summary contained in the chapters which follow.

3.2 Ground Processing System Functions

The functions of the MDPS Ground Processing System are to accept the raw input data as recorded on the airborne tape, to transform this data into a set of depth measurements at the observed passive points, and then to assign these measurements to points on a rectangular grid at any pre-assigned scale.

The computations have been divided into two programs, which, in general will be run separately. A "Depth Processing Program" takes its inputs from the airborne tape and produces depth outputs at the passively observed pixels. These outputs are stored on removable media such as disk-packs or computer-compatible magnetic tapes. The storage format is a listing of the depths in pixel-number order along the scan line preceded by a header giving the first and last pixel numbers in the scan, the geographic coordinates of the nadir pixel (aircraft position), the aircraft heading (which is 90° from the scan direction), the aircraft roll, pitch, and altitude, and such subsidiary information (e.g., gain settings, operator comments) as may be available and relevant. The output disks or tapes will be placed in the library and used, immediately or at any later time, as inputs to the second program.

The second ground processing program is called the "Grid Processing Program". Its inputs are the outputs from the "Depth Processing Program" and its outputs are a depth grid to any scale designated by the operator.

The Depth Processing Program is run once for every flight. The Grid Processing Program is run as often as required, to produce output grids to various scales. It will also be possible to construct a single grid from parts of several Depth Processing Program outputs.

The system has been designed so that the depth processing is performed at a speed equal to that at which the data was recorded. This means that the airborne tape is played back at the recording speed and the processing keeps pace. This insures that one day's flight data can be processed in one day, so there will be no backup of airborne tapes awaiting processing. The grid processing time will depend on the grid scale, but in most cases it should be substantially less, for a single grid, than the time required for depth processing. Since there will be no backup of depth processing, grid processing can be performed on the days following flight off days or in available half shifts following half-day flights.

3.3 Ground Processing System Hardware

To meet the throughput requirements described in Chapter 3.2, the Ground Processing System must use two processors working in coordination. The Master Processor will be a 32-bit conventional processor which will provide overall system management and control, and perform those computations involving complex equations or logic and relatively low repetition rates. The Pixel/Waveform Processor (PWP) will be a 32-bit Array Processor and will be used for the fast, highly-repetitive operations, notably the accumulation of sums and products of deep-water data in Phase I, the correlations used for finding the laser peaks in Phase II, and the pixel-by-pixel water-column length calculations in the passive phase. The recommended Master Processor is the VAX-11/750 from Digital Equipment Corporation. The recommendation for the PWP is the MARS 232R from Numerix Corp., which is designed to interface with the VAX via the Unibus.

The Ground Processing System Block Diagram is shown in Figure 3.3-1. In order to insure compatibility, all elements except the Pixel/Waveform Processor (discussed above) and the High-Speed Tape Reader will be standard VAX peripherals. The Interconnect will be a set of VAX Unibuses and Massbuses. The Mass Memory, to be used primarily as a buffer for delaying passive data with respect to laser data, will be a fixed-media (Winchester) magnetic disk drive. Working Storage will be 2 to 3 megabytes of VAX main memory. The Output Store will be either a pair of removable disk-pack drives or a pair of 6250-bits-per-inch magnetic tape drives. Not shown in the diagram is a System Disk for use with the VAX Operating System.

Table 3.3-1 summarizes the Ground Processing System hardware. It should be noted that this set of recommendations is based on available computers and peripherals as of December 1982. It should be borne in mind that the computer industry is very competitive and new products are

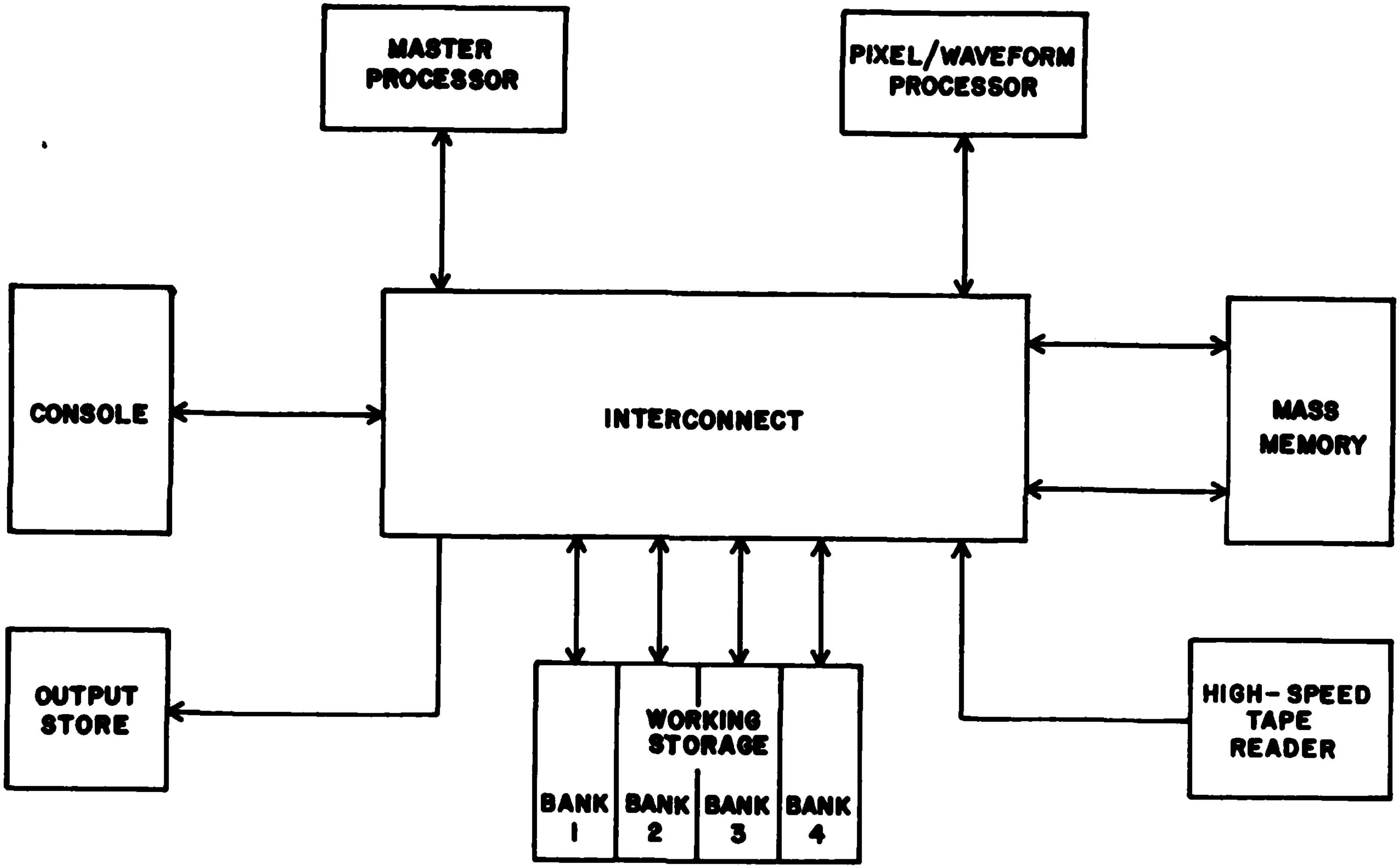

FIGURE 3.3-1
GROUND PROCESSING SYSTEM

Table 3.3-1

Ground Processing System Hardware

Functional Unit	Proposed Hardware
Master Processor	VAX-11/750 32-bit processor
Mass Memory	RM80 fixed-media magnetic disk drive
System Disk	RM03 removable disk-pack drive
Working Storage	VAX main memory (2 to 3 MB)
Output Store	RM05 removable disk-pack drives (2) (Alternate: TU78 mag.tape, 6250b/in.)
Pixel/Waveform Processor	MARS-232R 32-bit fixed-point array processor (Numerix Corp.)
High-Speed Tape	Recorder/reproducer from same source as airborne recorder (Ampex, Bell & Howell, Sangamo)
Console	LA 120 Console Terminal with TU58 tape cartridge unit
CRT Terminal	VT125 video terminal with graphics
Interconnect	Unibuses (2) and Massbuses (1 or 2)

Note: All hardware from Digital Equipment Corp., unless otherwise noted.

being announced almost daily. Therefore, it is highly recommended that when the system is ready for implementation the market place should be re-surveyed in order not to overlook newly-introduced elements which may be less expensive or otherwise superior to those on the current list.

For more detailed information on the Ground Processing System hardware, see the Third Interim Technical Report, Vol. I (A004-1), Chapter 4 and Appendices.

3.4 Ground Processing System Software

As discussed in Chapter 3.2, the Ground Processing System software is divided into two programs, the Depth Processing Program and the Grid Processing Program. Detailed specifications and flowcharts for these programs appear in A004-I, Chapter 3.

The Depth Processing Program is divided into 3 phases corresponding to the flight phases discussed in Chapter 2 of the present report. Several of these phases are further subdivided into processing steps.

In the Phase I processing, the deep-water data collected in Phase I of the flight is processed to calculate the terms which must be subtracted from the passive signal to remove the effects of sun glint, surface reflection, and upwelling light. This requires the calculation of the average deep water signals for each band and also correlations between the visible and IR bands, to be used in correcting for sun glint. In addition, the standard deviations of the deep water signals are calculated, to be used in subsequent phases to detect those passive bottom signals which are small compared to the deep water noise and should therefore be eliminated from further processing.

Since the required outputs are functions of the scan angle, the sums and correlations must be separately computed for each pixel number along the scan line. This means we require 5 sums (4 visible bands and 1 IR band), 5 sums of squares, and 4 sums of products of the visible and IR readings for each of 785 pixel numbers.

The pixel numbers must be offset to compensate for the roll of the aircraft. If the aircraft has a non-zero roll, the scanner element observing the nadir pixel (i.e., zero scan angle) will not be the center element but some element to the right or left, depending on the amount and direction of the roll. All other pixel numbers will be offset correspondingly. On the side of the aircraft which is rolled downward, the scanner field of view will not reach to the far end of the nominal scan line. On the other side, elements at the end of the scanner will have scan angles greater than 45° and therefore will not collect relevant data. The pixel number offsets must be applied not only in Phase I, but also to the use of the passive scanner in Phases II and III.

The computations for Phase II, the active/passive phase, have been divided into 4 steps. The first three steps are performed once for each laser pulse, and therefore have a relatively high repetition rate. The fourth step is performed once for each separate set of regression coefficients.

In Step 1, the digitized laser returns are analyzed to find the two peaks and, from their time separation, to determine the laser depth. To begin the process, the approximate positions of the peaks are found by locating local maxima in the raw digitized data. The search is conducted over a scan window whose width is sufficient to encompass both the surface and bottom peaks at the maximum depth which the system must measure and whose leading edge is displaced from the transmitted laser pulse in proportion to the altitude of the aircraft. The surface peak is found by searching forward (i.e., in the direction of increasing time delay) from the leading edge of the window. The search strategy for the bottom peak is more complex but in most cases begins in the neighborhood of the bottom peak found on the immediately preceding laser pulse.

When the two peaks have been found, stored templates are correlated with each as discussed in Chapter 2.4. Provision has been made to try up to 10 templates for each peak, to allow for variations in the shape of the reflected pulse due to bottom or water conditions. For a given template, various offsets on each side of the nominal peak position are tried and the offset producing the highest correlation between the template and the observed data in the neighborhood of the peak is determined. When a template is found for which the maximum correlation exceeds some threshold, the corresponding offset position is established as the actual peak position. If after all the templates have been tried none has been found which exceeds the threshold, the template having the maximum correlation is taken to represent the true waveform and its peak correlation offset position is taken as the return pulse peak. In order to avoid choosing a template with a very poor correlation, a lower correlation threshold is also established. If the best correlation is below this threshold, the laser point is discarded.

When the water is shallow, resolution of the peaks may be difficult. Therefore, two special cases have been provided for. In moderately shallow water, where the pulses are overlapping but distinguishable, provision has been made to use a special set of templates which discard the overlapping regions. When the water is very shallow, so that it is totally impossible to separate the returns, the laser shot must be discarded. The threshold at which this occurs will depend on the shape of the laser pulse and therefore could not be established in this study.

Once the two peaks have been established, the time difference between them is multiplied by half the speed of light in water to give the depth or, more properly, the laser water column length. If necessary, a tabulated bias correction may be applied to account for the effects of absorption and scattering of the light in the water.

In Phase II, Step 2, the passive signals (visible and IR) for the pixel corresponding to the laser point are determined. This determination involves 3 operations. First, the appropriate offset pixel is selected from the scan line corresponding in time to the laser pulse and the visible and IR readings at this pixel are extracted. Second, the surface and sun glint term is eliminated, using the parameters calculated in

Phase I. Third, the natural logarithms of the remaining bottom signals are determined.

In Step 3, we use the outputs of Steps 1 and 2 to update running sums which will be required for the regression coefficient calculations. For each of the 5 outputs of the preceding steps (laser depth and the 4 derived visible band signals) we have been accumulating a running sum, beginning with the first laser point in the zone covered by the current set of regression coefficients. We now update each of these sums by adding in the newest term. In addition, we take all possible products of these 5 terms, including squares, and add them into respective sums of products which we have also been accumulating. When the last point to be used in the particular regression set has been reached, the accumulated sums are used to calculate various statistics required in the computation of the regression coefficients.

Early in the MDPS study it was assumed that no more than 3 visible bands would be used in calculating any one set of regression coefficients. The software specifications for Phase II, Step 4 have been based on this assumption. However, there would be no problem in extending these specifications to the 4-band case if this should be deemed desirable.

The calculation of the regression coefficients involves only a small set of arithmetic operations on the outputs of Step 3. However, it is necessary first to determine how many and which of the 4 visible bands we are going to use. As was pointed out in Chapter 2.3, the number of bands used should, ideally, be equal to the number of bottom types in the regression area. Using a number of bands smaller than the number of bottom types is feasible, although it will introduce some errors. However, the use of a number of bands greater than the number of bottom types can lead to totally meaningless results. To avoid this problem, we generate a function of the Step 3 outputs which, theoretically, will vanish if the number of bands is too large. In practice, the presence of noise will usually prevent this function from going precisely to zero, so we test its absolute value against a small positive threshold. If the threshold is not exceeded, we conclude that we must use a smaller number of bands.

Starting with the 3-band case, we perform the threshold test discussed in the preceding paragraph for each combination of 3 of the 4 visible bands, a total of 4 combinations. If no combination passes, we have too many bands and we drop to the 2-band case, to be discussed below. If one or more combinations of 3 bands exceed the threshold, we calculate the regression coefficients for each such passing set. Using these regression coefficients, we calculate for each set, a statistical measure called the "multiple correlation coefficient". Each of these multiple correlation coefficients is tested against a threshold which depends inversely on the number of laser points used in the regression process. If for one or more sets of bands the multiple correlation coefficient exceeds this threshold, the set with the highest multiple correlation is chosen and the corresponding regression coefficients are carried into Phase III. If no set exceeds the threshold, it is concluded that there is no set of 3 bands for which the noise levels, including the laser noise level, are sufficiently small to provide a satisfactory set of regression coefficients with the number of laser points used. Therefore, two options are available. One is to increase the size of the data set by going back to Step 1 and processing additional laser points. The other is to drop down to a 2-band case.

If the 2-band case is entered, by either of the paths discussed above, the procedure followed is essentially identical to that used for 3 bands. Six combinations of 2 out of 4 bands must be considered. First, a test is made to insure that there are at least 2 different bottom types in the regression area. Then the pair of bands with the largest multiple correlation coefficient is chosen and if this coefficient exceeds the threshold the corresponding regression coefficients are used.

If there is only one bottom type, or if no set of 2 bands produces a satisfactory multiple correlation coefficient, we go to a single-band mode.

In Phase III, the passive readings for each pixel on each scan line together with the parameters calculated in Phases I and II are used to determine the full set of passive-only depths. The procedure used in this part of the program follows precisely the theory discussed in Chapter 2. The program divides into 3 branches, depending on the number of passive bands used in the particular regression area, as determined in Phase II.

For each scan line, the program also reads the position and attitude data from the tape and calculates nadir coordinates and other coefficients which will be required by the Grid Processing Program.

In some scenarios, a single scan line may pass through 2 or more regression zones or, as they have been called in the program specifications, water types. It will then be necessary to use different sets of regression coefficients on different parts of the scan line. It has been assumed that these water-type boundaries are pre-entered into the system, either graphically or numerically. A routine has been included in the Phase III software to be used, for each scan line, to locate the "boundary pixels" i.e., the points, assumed to be no more than one on each side of the nadir, at which the regression coefficients must be changed.

The Grid Processing Program begins with a linearization process. Since the pixels along a single scan line have constant angular separation as seen from the aircraft, their linear separation along the surface varies, being approximately twice as great at the ends of the line as it is at the nadir. The first step, therefore, is to convert the 785-point angular set to an evenly-spaced 1001-point linear set. The linear set will have one pixel centered at the nadir and 500 on each side, with the pixel dimension along the scan line equal to the aircraft altitude divided by 500.

In the programming specifications presented in Third Interim Technical Report, the linear set is created by interpolating both depth and position between adjacent points of the original angular set, using a stored table of interpolation factors. If, however, a nearest-neighbor procedure is preferred, this can easily be implemented by using a table relating each element in the linear set to its nearest neighbor in the original set and assigning the corresponding original-set depth to the linear position. This actually requires less computation than the interpolation procedure described in the specifications.

After the set of points along the line has been linearized, intermediate points both along and between lines can be created to any desired density. In the specifications, the depths at these points are determined by linear interpolation, but clearly a nearest-neighbor procedure is also feasible.

In the final step, the positions are converted to North and East coordinates and the depth associated with each position is assigned to the nearest grid point. If the set has been made sufficiently dense, the probability that any given grid point will not receive an assignment is negligible. If two or more depths are assigned to the same grid point, the specified program will choose among them by selecting the last assignment. An alternative would be to accept the smallest depth, thereby insuring that no hazard to navigation would be likely be missed.

3.5 Airborne Processing and Recording System Functions

The Airborne Processing and Recording System has three major functions. One function is the control and synchronization of the airborne sensors, namely, the Multispectral Scanner, the laser depth measurement system, and the position and attitude measurement system. The second function is the recording of the digitized sensor data on high-density magnetic tape, for analysis and processing on the ground. The third is the computation of sample depths and the performance of statistical calculations by means of which the operator can ascertain the quality of the data being collected. The control and synchronization function will depend on the detailed characteristics of the sensors and therefore all that could be done in the MDPS study was to allow computer capacity for this purpose. The other two functions were considered in detail and the results of these studies are described in the three Interim Technical Reports.

3.6 Airborne Processing and Recording System Hardware

Figure 3.6-1 shows the major elements of the airborne system. The Multispectral Scanner, Laser, INS/GPS, and Altitude System comprise the sensors. It is assumed that all of these elements are designed to provide digitized outputs. The remaining hardware elements shown in the block diagram form the Airborne Processing and Recording System.

The system element providing the primary control and airborne processing functions is the minicomputer. A number of computers were considered for this function but the eventual recommendation, in the third Interim Technical Report, was the PDP-11/44M, a militarized version of the widely-used Digitial Equipment Corporation PDP-11/44. The PDP-11/44M is part of a family of militarized PDP-11s which has been given the family military designation AN/UYK-42(V). The reasons for this choice of minicomputer are spelled out in Chapter 2.3 of Vol. II of the third Interim Technical Report (A004-II).

The Laser Processor is a small specialized machine for performing the correlations necessary to extract the depth information from the digitized laser data. (See Chapter 2.4 of this report.) It can be realized with available LSI chips, as discussed in the third Interim Technical Report. The Interim Report also discusses two alternatives. One is to use a commercial array processor, preferably of the same make and model as used in the Ground Processing System. While this processor is not a militarized design, it is a compact package which could probably be mounted to function in the survey aircraft environment. The other alternative is to restrict the in-flight use of the laser data in such a way that the depth extraction function can be assigned to the Minicomputer and the Laser Processor eliminated altogether. These alternatives should be studied before the system is implemented.

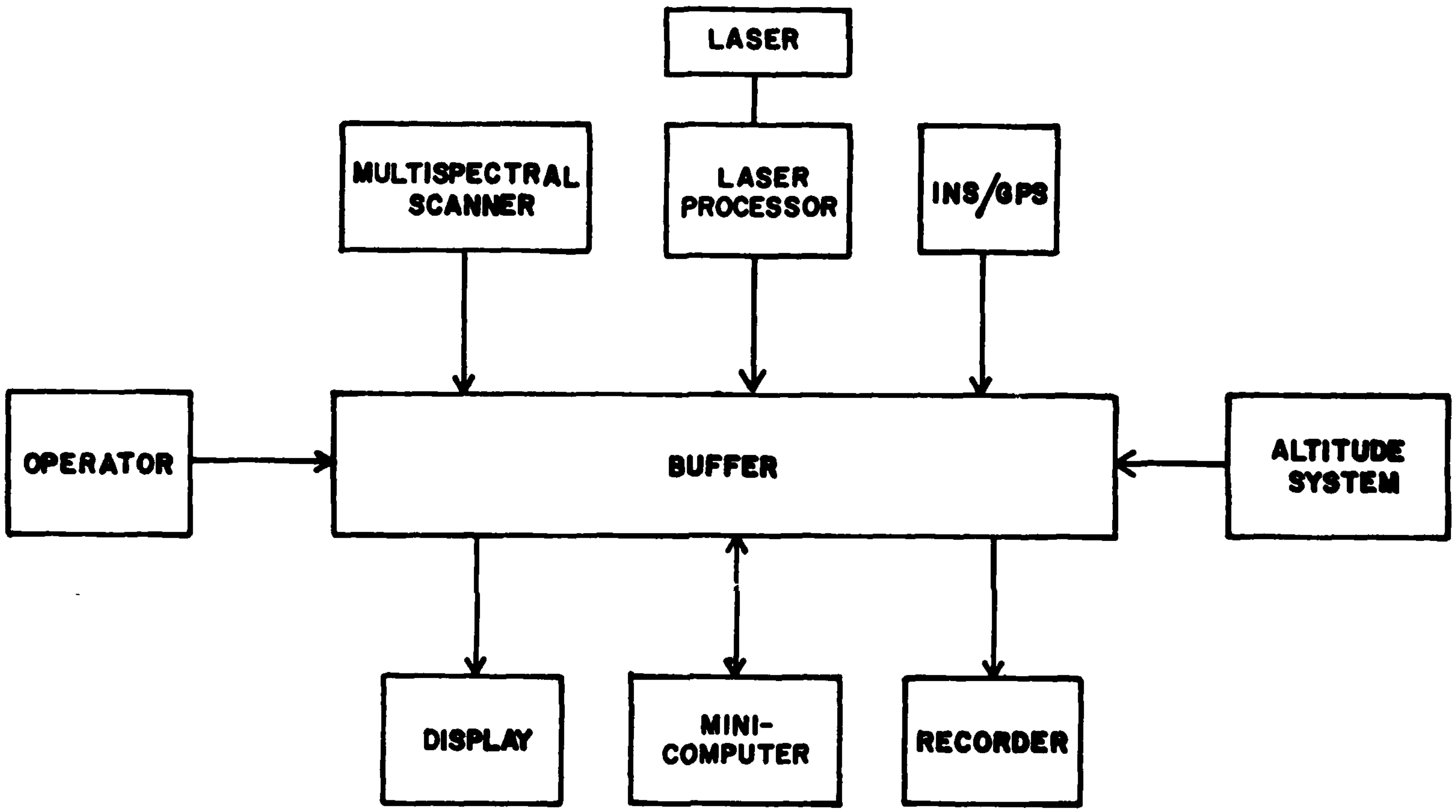

FIGURE 3.6-1
AIRBORNE SYSTEM

The buffer will be used primarily for ordering and integrating the flow of data to the recorder and storing samples of raw data to be processed for the airborne display. A militarized 8-inch Winchester disk drive has been recommended for this function. The disk would also serve as the system disk for the minicomputer Operating System.

The display recommended is a 640 x 480 raster-scan color graphics system with an 8-bit-deep refresh memory. An airborne system developed and built by W. W. Gaertner Research, Inc. is recommended. The display will be imbedded in a specially-designed console providing the operator with the necessary facilities for controlling the system and sensors and selecting the information to be displayed. The recorder will be a 28-channel high- speed digital tape system. Candidates are the Ampex AR-1700, the Sangamo SABRE V, and the Bell & Howell M14-L. The system cost estimate (see Chapter 4) has been based on the assumption that a second recorder will be provided as a backup.

The hardware is summarized in Table 3.6-1. For more detailed information see Vol. II of the third Interim Technical Report, Chapter 4. The Appendices to the referenced Volume contain selections from the manufacturer's literature on the various elements. The Minicomputer is covered in Appendix A, the LSI chips for the Laser Processor in Appendix B, the Display Symbol Generator in Appendix C, and the disk drive recommended for the buffer in Appendix D. A summary of the airborne tape recorder characteristics is presented in the Interim Report as Figure 4.5-1.

Table 3.6-1

Airborne Processing and Recording System Hardware

Functional Unit	Proposed Hardware
Microprocessor	PDP-11/44M (Norden Systems)
Laser Processor	Special processor using AMD 29500 series LSI signal processing chips
Console and Display	Digital Symbol Generator, color monitor, and custom console (W. W. Gaertner Research, Inc.)
Recorder	Ampex AR-1700, Sangamo Sabre V, or Bell & Howell M14-L
Buffer and System Disks	RDS4502 (Miltope Corp.)

3.7 Airborne Processing and Recording System Software

The software for the Airborne Processing and Recording System is specified in detail in Vol. II of the third Interim Technical Report, Chapter 3.

The processing for Phase I and Phase II is almost identical to that for the corresponding phases in the Ground Processing System. The major difference is that in the airborne system not all of the data is processed. This is done to meet the throughput constraints of the airborne minicomputer. The amount of processing is entirely adequate for the limited qualitative purposes for which the data is used in-flight. Needless to say, all of the data is stored on the tape for use in the ground system.

In Phase III, a limited set of depths is processed for display. Two modes are offered, to be selected by the operator. In the Spot Mode, a depth chart is processed and displayed on the CRT for a small fixed area. This is not, of course, a real-time display, but the delays will be small enough to allow the operator to take corrective action or change the flight plan if the displayed chart appears to be unsatisfactory. In the Scroll Mode, the data is processed in real-time but the scale is large, so the depth calculations need be made for only a small fraction of the pixels. The data are then scrolled downward on the screen, new data entering at the top and the old data being dropped off at the bottom. This provides a map moving along the track of the aircraft. To provide a uniform scale, nearest-neighbor linearization is used.

In the airborne system, the display may also be used to provide the operator with raw sensor data and statistical information which can be used to judge the quality of the survey. Statistics which are computed by the software and which may be presented at the election of the operator include the standard deviation of the deep water reading, the regression coefficients, the multiple correlation coefficients for each set of bands, and the computed attenuation coefficient in each band.

4. COST ANALYSIS

4.1 General

The preliminary cost estimates in Chapters 4.2 and 4.3 are intended to provide information to the Sponsors for planning purposes. They are based on the system specifications as presented in the third Interim Technical Report. They were arrived at by careful consideration of the effort required for hardware development and procurement and system integration, step-by-step analysis of the programming requirements, and discussions with the vendors, including, in some instances, formal quotations. They do not, however, constitute a development "price", even on a budgetary basis. Such an estimate can be made only in the context of a total active/passive bathymetry system development, with a formal specification, work statement, schedules, and documentation requirements.

The analaysis is for a single system, one Airborne Processing and Recording System and one Ground Processing System. Additional identical systems will obviously cost less. The costs cover the design and implementation of the processing (and recording) hardware only. The airborne system cost does not include sensors or aircraft and the ground system cost does not include the site. Installation costs are not included in either case. It is assumed that all of the sensors will provide data in digital form, so that A/D converters are not included in the Airborne Processing and Recording System hardware.

The software design will depend, at some points, on the characteristics of the sensor outputs. It is assumed that the necessary information will be provided, either by the Sponsors or by the contractors developing the sensors.

4.2 Ground Processing System

Hardware of the type required for the Ground Processing System tends to move rapidly downward in cost. The estimate below reflects what is believed to be the latest costs for the DEC equipment. However, lower prices may be available at the time the system is implemented.

VAX and peripherals	$185,000
Array processor	50,000
High-speed tape reader	110,000
Software (24 mm)	176,000
Hardware engineering (15 mm)	110,000
Drafting and documentation (12 mm)	62,000
TOTAL	$693,000

The VAX and peripherals includes all equipment in Table 3.3-1 except the array processor and the tape reader. It also includes the VAX/VMS operating system. The array processor includes all its standard software. Hardware engineering covers procurement, integration, and laboratory test, plus the design and construction of a buffer for the tape reader.

4.3 Airborne Processing and Recording System

The cost analysis for one Airborne Processing and Recording System is as follows:

Minicomputer	$100,000
Buffer (disk)	50,000
Tape readers	210,000
Console and display (12 mm)	108,000
Laser processor (8 mm)	70,000
Software (21 mm)	154,000
Hardware engineering (12 mm)	88,000
Drafting and documentation (12 mm)	62,000
TOTAL	$842,000

It is assumed that there will be two tape readers on board; one for backup. Subtract $100,000 if backup is not required. The console and display cost includes display firmware. Laser processor cost covers design and construction. The software cost is estimated at slightly less than that for the Ground Processing System because the specifications overlap. Hardware engineering covers procurement, integration, and laboratory test.

5. ERROR ANALYSIS

5.1 Procedure

A preliminary error analysis was performed in order to obtain an understanding of the ability of the system to measure depths to the required accuracy.

The method used was Monte Carlo simulation. The regression coefficients, for a 3-band case, were calculated over a scene having a distribution of depths from zero to 30 meters and three bottom types. The bottom types and corresponding reflectances are tabulated below. Reflectances are in percent and wavelengths in nanometers.

Bottom type	Wave length		
	450	500	550
Sand	12	15	20
Shoal grass	4	5	9
Turtle grass	3	3	5

The water type was Jerlov IB, having attenuation coefficients, per meter, of .04 at 450nm and 500nm and .07 at 550nm.

For the regression coefficient generation, a "scene" was simulated comprising 450 points. The scene contained the three bottom types in approximately equal numbers and a distribution of depths from 0 to 30 meters. The laser depth at each point was derived by taking the "actual" depth and adding a (positive or negative) error generated by an unbiased random-number generator. The scanner signals at each point were derived by using equation (1) (Chapter 2.1) with V_{0i} equal to zero and adding an unbiased ramdom error. The error generation procedure was such that the errors were uncorrelated between passive bands, between active and passive, and from point-to-point.

Regression coefficients were calculated using the full set of 450 points and also using two different-sized subsets, taking care that each subset included all bottom types and a representative range of depths. Since in the example the number of bands is equal to the number of bottom types, there exists a set of "true" regression coefficients, which will produce computed depths independent of the bottom type (for the 3 bottom types in the scene). See Chapter 2.3. If the number of points is sufficiently large, the derived regression coefficients should be a good estimate of these "true" values. Thus, a comparison of the "true" values with the regression coefficients obtained from the Monte Carlo simulation using point subsets of various sizes indicates the approximate number of laser points required in the regression set.

To obtain the RMS depth errors, a Monte Carlo analysis was applied to a simulated Phase III (passive) run, using the regression coefficients obtained using all 450 points. Errors were derived for depths of 0, 10, 20, and 30 meters.

5.2 Results

The table below shows the values obtained for the regression coefficients using various numbers of points. The standard deviation of the scanner error was taken as equivalent to a reflectance of .005%. The standard deviation of the laser error was taken as 1 meter.

Coefficient	"True" Value	450 pts.	135 pts.	45 pts.
b_0	-5.488	-5.729	-5.150	-3.865
b_1	-11.818	-12.277	-11.122	-9.345
b_2	20.674	21.049	20.078	18.310
b_3	-12.193	-12.154	-12.230	-12.014

Comparing the derived values with the "true" value, we conclude that for this case the optimum numer of points for the regression analysis is in the range of 200 to 300, i.e., 10 to 15 seconds of data at a laser pulse repetition rate of 20 pulses/sec. This depends primarily on the scanner error; runs made with other error values show that for larger scanner errors the convergence to the "true" value will be made slower, even if the laser errors are smaller.

The RMS depth errors were determined using the 450-point coefficients given in the preceding table. The results are tabulated below. Depth and error units are meters.

Depth	Bias	Standard Error	Total RMS Error
0	-.0202	.0247	.0319
10	-.0111	.1006	.1012
20	-.0331	.2291	.2315
30	.0264	.3903	.3912

The biases result primarily from the regression coefficients and would be even smaller if the "true" values were used. Even with the 450-point values it can be seen that the effects of the biases on the total RMS errors are negligible. Thus we conclude that if the system is properly used, the errors in the depth measurements will be due almost entirely to the errors in the scanner. This is confirmed by theoretical considerations.

When the bathymetric system implementation is undertaken, an error analysis covering a wider range of cases should be undertaken in order to establish the design requirements for the scanner. In view of the results discussed in this chapter, the laser errors need not be considered, for this purpose, and the regression coefficients can be set equal to the "true" values. Then the depth error can be approximated in closed form as a linear combination of the errors in the three scanner bands, which will make it possible to obtain large numbers of results with much less computation than the Monte Carlo analysis required. The effects of actual scanner noise characteristics, which are probably dependent to some extent on signal strength, should be studied.

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