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OPERATING SCENARIO FOR A HYDROGRAPHIC AIRBORNE LASER SOUNDER (H--ETC(U)
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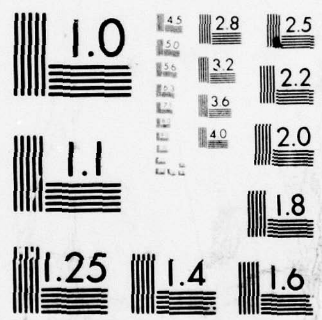

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NORDA TECHNICAL NOTE 34

LEVEL II

OPERATING SCENARIO FOR A HYDROGRAPHIC AIRBORNE LASER SOUNDER (HALS)

H. J. BYRNES
Mapping, Charting & Geodesy
Development Group

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NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY
NSTL Station, Mississippi 39529

ABSTRACT

This note is intended to acquaint interested parties with the anticipated deployment of a Hydrographic Airborne Laser Sounder (HALS). Data acquisition, data processing, data reduction rationale, data density, test results, and environmental considerations are covered. The document is intended primarily as presolicitation information for the HALS procurement.

CONTENTS

ILLUSTRATIONS

I. INTRODUCTION

This operating scenario is intended to acquaint interested parties with the anticipated deployment of a Hydrographic Airborne Laser Sounder (HALS). An operating synopsis providing an overview of data acquisition and data processing is contained in section II. Section III contains a rationale for the data processing techniques to be employed in HALS data reduction. Section IV treats the question of data density vs. chart scale. Section V describes test results acquired via both simulations and field data; additional test results from field data can be found in the appendix. Some environmental considerations appear in section VI.

This document has been prepared primarily for the purpose of providing prospective contractors with a more complete concept of what is desired via the Purchase Description covering the performance characteristics of HALS. The scenario presented relies heavily on the system concept employed in the NASA Airborne Oceanographic Lidar (AOL) Tests. The contractor is not limited to the concepts presented here; he is invited to propose other concepts.

II. OPERATING SYNOPSIS

Two modes of operation are anticipated in HALS deployment. Mode I is anticipated as an operational mode where NAVOCEANO would employ the system on a production basis. Mode II is anticipated as a diagnostic mode where laser return waveform information would be recorded occasionally for the purpose of defining an improved bottom pulse recognition and placement algorithm. Data from Mode I operations would feed directly to the NAVOCEANO chart-making process, whereas data from a Mode II mission would be delivered to NORDA for processing and analysis.

The use of a HALS system is tied directly to present NAVOCEANO near-shore surveys, and therefore imposes only slight procedural changes on present operations. Currently NAVOCEANO near-shore survey ships are equipped with an H2D helicopter that is used primarily for deployment and servicing of NAVAIDS.

The HALS will be intermittently installed in that helicopter to perform missions near the beach where normal soundboat safety or performance might be compromised by shallow water, and into deeper water as environmental conditions permit. The primary task for the HALS on these missions will be to acquire chart quality data satisfying survey requirements. The mission duration for the HALS system will not exceed two hours.

HALS installation would begin with the survey ship on site after the NAVAIDS are in place and the helicopter is available for a few days. Depending on the area, the HALS may complete its mission in only one day; however, maximum utilization requiring several days is anticipated.

The HALS modules will be removed from their crates, handcarried to the aircraft and bolted to the aircraft frame. Interconnecting component and power cables will be installed and the system turned on for checkout. Computer programs will be fed to the computer and diagnostic procedures will be run through. Optical alignment will be checked to determine if alignment is correct. The installation and checkout procedures, including realignment when necessary, will require less than six hours. The HALS is then turned off to await appropriate time and weather--missions are planned near dawn or dusk for improved performance.

Prior to any mission, a survey plan delineating survey tracks employing the NAVAIDS and survey geometry will have been prepared via the shipboard computer. The beginning and ending positions of the survey tracks will serve as flight control points for those tracks assigned to HALS.

A typical Mode I mission begins with the aircraft in a stand-by posture (i.e., full gas load on board and crew ready). The HALS is turned on, computer programs loaded, mission control points inserted, and checkout procedures run through.

The aircraft lifts off, rises to an altitude of 500 feet, and sweeps over deep water while operating the laser to acquire calibration data. The aircraft heads for a landing site near a NAVAID, lands (section II.A presents several options to gyro alignment), aligns attitude and heading gyros, lifts off, rises to an altitude of 500 feet, and heads for the first flight line control point to begin the survey. The computer is now processing ranging information received from the NAVAIDS to provide flight directives to the pilot in the form of instructions as to the right and left extremes of the flight path and distance to flight line control points.

While approaching the control point, the HALS operator monitors the oscilloscope and control display to evaluate performance. When the control point is reached, the operator starts the recording system and continues monitoring. As the mission continues the computer processes navigation data, computes Dead Reckoning positions, and directs the pilot to the end of the survey track. At the end of each track, the operator stops the data recording and restarts when arriving at the next starting control point.

At the completion of the planned mission, or when performance deteriorates to the degree that bottom returns are no longer being received for an extended period of time, the aircraft returns to the NAVAID landing site to again align the gyros.

The aircraft returns to the ship where data tapes are processed through a "quick look" program to determine (1) the approximate rough coverage and (2) whether an immediate additional mission is required. When the HALS has completed all its missions for a particular survey site and data have been evaluated, the system is removed from the aircraft and stored in packaging crates.

Post-flight data reduction (as indicated in Fig.1) begins as data tapes from the helicopter become available. A data tape is read, deblocked, merged with external inputs, and formatted for an optimal solution on the laser slant ranges. The computer performs a minimum variance solution, generating x,y coordinates relative to the aircraft position, and depth information which has been corrected for surface waves. The relative coordinates are added to aircraft position and outputted to tape and listing as the processing progresses.

An along-track display is also generated as the processing continues. The display permits the operator to evaluate bottom complexity and data integrity. If the data appear sound and the "bottom" flat, the operator merely scans the listing and extracts data to be merged, or plotted, on the chart. If the data integrity appears unstable or the "bottom" complex, the output tape will be read back as input for a second processing pass (section III.B presents more detail on this procedure). The second pass will process the x,y,z information into a minimum variance grid and select the shoalest depths at densities relative to the intended chart scale. The second pass creates an additional listing and a tape containing grid elements, shoals and covariances.

HALS DATA REDUCTION

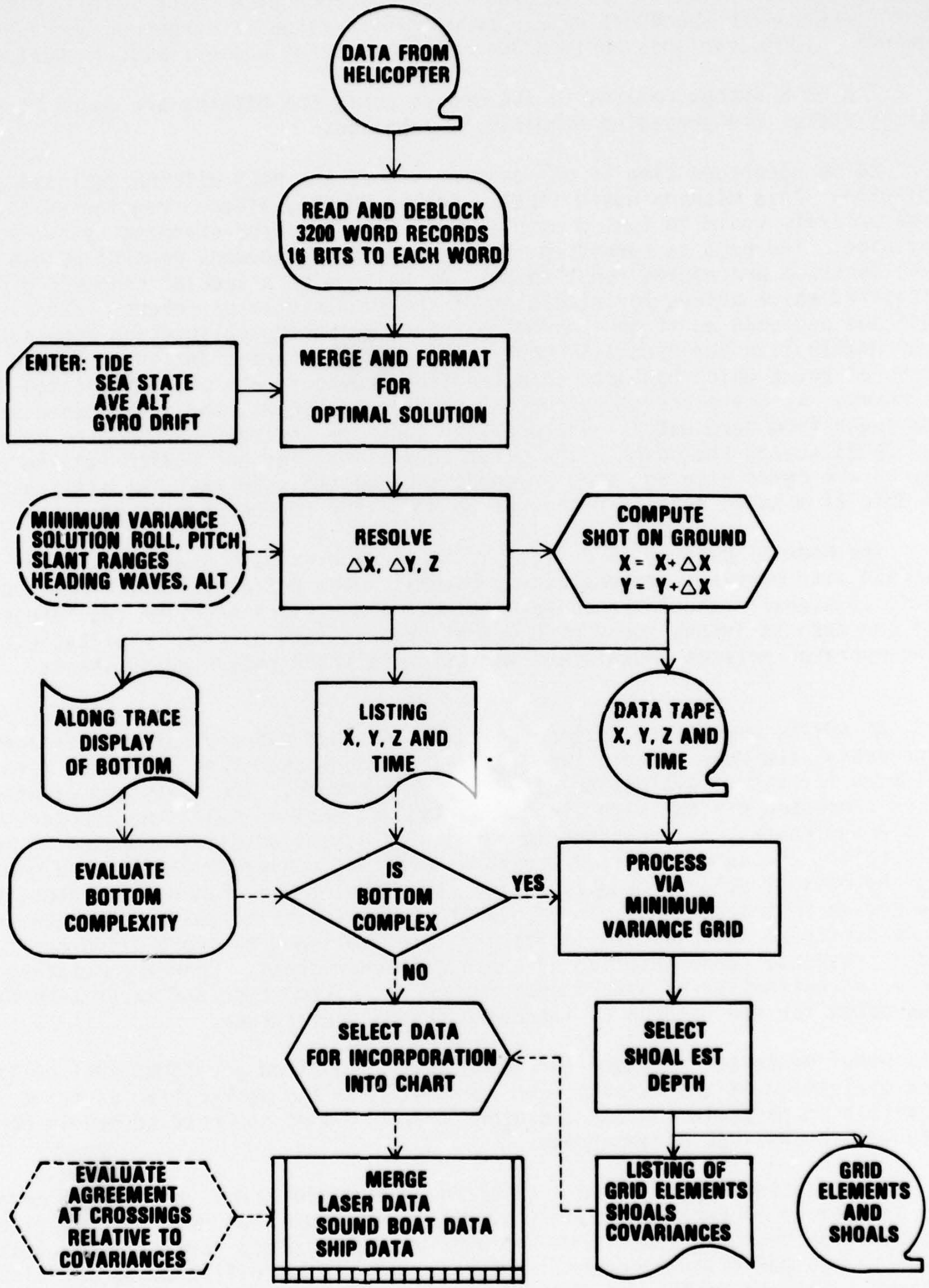

Figure 1. HALS Data Reduction

From this new listing the operator plots all of the shoalest depths and an appropriate sampling of grid depths in conformance with chart scale. After data have been merged with soundboat data, the operator evaluates agreement where overlap occurs. The covariance derived during the gridding process aids in that evaluation.

The HALS system remains in its crates until the NAVAIDS are moved to open a new site; there, the preceding scenario is repeated.

At an opportune time at one or more sites, the HALS will be assigned a Mode II mission. This mission would ideally follow shortly after a regular survey mission. The aircraft would be fueled with a small fuel load and standing by for a 15-minute mission. The HALS is turned on, standard programs loaded, control points inserted and checkout procedures run through. At this point a special computer program is inserted which allows for recording of the complete laser return. The aircraft lifts off and proceeds as if on a normal mission, gathering calibration data and landing at the NAVAID site for gyro alignment. The aircraft then transits to the initial control point which has been selected from previous data which indicated no bottom returns. As the aircraft approaches the control point, the pilot maneuvers so as to approach from deep water. The operator turns on the recorder and the mission proceeds toward the beach. The pilot then flies for the NAVAID landing site where gyros are again aligned, then proceeds back to the ship with the mission completed. A Mode II mission data tape is sent to NORDA for further processing.

The Mode II mission is desired at least once in each new survey area. Moving the NAVAID site merely to extend survey coverage does not constitute a new area. The Mode II scenario should be repeated at different sites any time the integrity of the data is inconsistent with visual observations of water clarity, etc., or when the operator notices unexplained variation in laser return pulse shapes.

At NORDA, depths are recomputed to assure that onboard software is operating correctly; the Mode II data tape is read and deblocked, and digitized waveforms are plotted for visual evaluation of system performance. The digitized waveforms are then processed via the same algorithm that was used on board the aircraft to determine depths, and are then compared with depths actually computed on board the aircraft. The same digitized waveforms are then processed via other algorithms, such as the optimal pulse recognition algorithm developed by Fagin Associates, to determine if improvements can be made to the on-board software. As data are acquired from different survey areas, a library is established to store different types of laser response representative of those different areas. Upon accumulating sufficient data, an evaluation of system performance vs. bottom type and water turbidity will be conducted for the purpose of improving system performance.

Other processes intended for the Mode II digitized waveforms include isolation and evaluation of the water column backscatter. The backscatter contains information relative to particle content and other properties of interest to people conducting studies in physical oceanography.

Other intended uses of data gathered in both the normal production mode and Mode II operations concern surf modeling. It is expected that near shore surface wave information can be gleaned from the HALS aircraft to sea surface laser measurement via the optimal filter process. The wave information will then be correlated with the measurements of the water depth and used in validating surf models.

Mode II operations and subsequent analysis infer no reprocessing of data already collected via the Mode I production missions. In a production mode, data delineating the laser returns will not be recorded on magnetic tape and therefore will not be available for massaging at a later date. The primary purpose of Mode II operations is to improve the pulse recognition algorithm which will be installed in the initial phase of the HALS program.

A. GYRO ALIGNMENT

The necessity for good heading (re. gyro alignment) information is dictated by the geometry of the anticipated scan pattern and the employment of heading for providing pilot flight directives. Heading quality becomes critical as swath width increases. The options relative to gyro alignment procedures will be dictated first by the type of gyros selected for the HALS system, and second, by the positioning quality dictated by survey requirements.

The type gyro selected for heading will have primary impact on alignment procedure, since the gyro could be either north-seeking (self-aligning) or spacial oriented (requiring external alignment). Selection of gyro type has been left to the contractor, since size, weight, cost, and operating complexity should be considered in system proposals.

The selection of a self-aligning gyro would mean that alignment could be performed anywhere that the helicopter could set down on solid earth, and would greatly simplify the alignment operation. At the beginning of the mission the operator would let the gyro align itself; at mission end, the operator would merely note the difference before and after alignment and record the difference as gyro drift.

A gyro requiring external alignment would presuppose a surveyed azimuth installed by the survey party at the NAVAID site, and the addition of some optical alignment equipment with the HALS package. The procedure for external alignment will be such that the helicopter need not position itself precisely over any given spot, since precise maneuvering is somewhat difficult.

The anticipated external alignment would have a crew member set a tripod over the azimuth reference line, sighting along the reference line, then to the gyro unit. The gyro unit would have a mirror arrangement such that the sightings from the tripod to the gyro unit and from the gyro unit to the tripod are co-linear. After solving the geometry for the true heading, the operator would then slew the gyro to the correct reading for the start of the mission. At the end of the mission, the same procedure would be exercised except for slewing the gyro; at mission end the operator would merely record the gyro drift for later use.

Where the quality of positioning becomes less important (as dictated by survey requirements) the external alignment procedures could be accomplished on board ship. In these instances markings on the helioport could serve as reference points, and the ship's Mark 19 gyrocompass, with appropriate repeater, could serve as the azimuth line.

In many instances it should be possible to utilize the advantages of a magnetic slaved gyrocompass. Magnetic variation charts are available for most anticipated operating areas, and where updating is required, a few measurements near the NAVAID sites can be extrapolated to the operating area.

Numerous other procedures for alignment could be discussed, but further treatment is beyond the scope of this paper; however, it should be understood that there is no intention to impose a calibration procedure which is so cumbersome as to dilute HALS system efficiency. In areas where NAVAID sites are distant from a survey area (as may be the case, on occasion, when employing a medium range NAVAID), it becomes impractical to perform calibration at the NAVAID site because of the limited fuel load of the helicopter.

B. SATURATION SURVEY

Occasionally the HALS may be called upon to perform other special missions for purposes of validating or verifying suspect bottom structure. On these occasions it may be desirable to narrow the swath width to about 50 feet so that the suspect area can receive saturation sampling. It may even be desirable, on occasion, to hover over a particular site or to maneuver in some constrained search pattern.

With a narrow swath, position errors attributable to aircraft attitude and heading become less significant; this reduces significant impacts on both alignment procedure and on data processing. Gyro alignment can be accomplished on board ship or possibly even ignored. Data processing could be simplified to direct solutions of the geometry or also ignored.

The assumption for all the above, of course, is that position of the suspect bottom structure is already known from previous survey efforts either by HALS or via soundboat surveys. The only purpose for the saturation survey is to validate the existence of the structure and to determine minimum depth and areal extent; for those purposes, merely having the computer search for a cluster of minimum depths should be adequate.

C. NAVAID CALIBRATION

The Operating Synopsis as described in section II presumes a HALS operating in conjunction with a short range NAVAID. The most probable deployment anticipated for NAVOCEANO near shore surveys would involve a medium range NAVAID operating in either range/range or hyperbolic mode. Under these circumstances, calibration of the HALS receiver would be required.

Assuming the shipboard receiver to be already properly calibrated, the shipboard reading should be transferred to the HALS receiver prior to helicopter lift-off. The transfer reading will be corrected for the difference relative to the location of the respective antenna. As the helicopter proceeds toward the beach for gyro alignment, a landmark will be selected and NAVAID readings recorded--as the mission progresses, the helicopter may return to the selected landmark and check calibration as required.

III. DATA LOGISTICS

An important consideration in resolving position and depth from HALS observations is that we are dealing with multiple error sources. The error sources consist of aircraft's own position, altitude, attitude, and sea surface, as well as the laser slant range measurements and a multitude of environmental conditions which can cause error in those measurements.

The aircraft position error is directly dependent on the quality of the NAVAID employed in the survey. Where high quality data are required, a high quality NAVAID should be employed. There may be some possibility of improving the aircraft position via smoothing algorithms, assuming that the offending error has a random distribution, but this technique is being considered only for situations where medium range NAVAIDS are employed (see section III.C for further discussion). Smoothing techniques could also be employed on the optimal solution concerning the aircraft to sea surface slant ranges, but the technique is not being considered for this particular application at this time, and is not part of the post-survey processing development.

To minimize the effect of error sources from altitude, attitude, sea surface and slant range measurement from aircraft to sea surface, an optimal solution, which operates in a minimum variance sense, has been developed. The optimal solution will be described in the next section.

Error sources relating to environment are shown in two ways: (1) the bottom return shape is perturbed in a manner such that the tracking algorithm on board the aircraft misplaces the pulse, and (2) the pulse is reflected from something other than the true bottom. If we assume these to be random occurrences, then the solution is redundant measurements and the proper processing of that redundancy. This will be further discussed in the section covering data gridding.

A. THE OPTIMAL SOLUTION

This portion of the software treats the processing of laser slant range measurements related to the distance between the aircraft and the surface of the water.

To visualize how the optimal solution works, picture a laser pulsing at 400 Hz. The laser seeps through 360° at 5 cycles per second creating a moving elliptical pattern on the surface of the water. Each sweep through 360° provides 80 pieces of slant range information from the aircraft to the surface of the water. Under static conditions, at any given altitude and azimuth, the slant range measurement from aircraft to sea surface could be precisely computed. The major axis of the projected ellipse would align perpendicular to the aircraft heading and the minor axis would align parallel to the aircraft. Under dynamic conditions, slant range could still be precisely computed if pitch, roll, altitude and sea surface are known. The trouble is, that even with an inertial system, there are errors which would affect the slant range computation. If the problem is turned around (upside down, as it were), the difference between the slant range measurement and what would be computed for a given altitude is actually a measure of pitch, roll, altitude error and sea surface. That is what is done in the optimal solution.

A "current best estimate" of altitude and attitude are used to compute an estimate of the next observed slant range to mean surface. The difference between the observed and estimated slant range is then treated as an error and is processed through an algorithm which allocates portions of the error relative to the assumed magnitude and correlation times of the error propagation model. The algorithm directs the error to propagate in a minimum variance sense to the following: (1) error in slant range measurement, (2) aircraft altitude, (3) aircraft pitch, (4) aircraft roll, and (5) sea surface.

The same current best estimates, as above, of altitude and attitude are used to compute the laser spot on the bottom relative to the aircraft. The sea surface estimate removes error from the depth measurement, thus completing the optimal solution.

The operation is something like an interactive process:

1. Assume some value for pitch, roll, altitude and sea surface.
2. Compute a slant range.
3. Subtract observed from computed.
4. Allocate differences, some to pitch, roll, altitude, etc.
5. Compute next slant range.
6. Subtract.
7. Allocate.

The whole purpose of the optimal solution is that good roll, pitch and altitude are needed for positioning the laser observation relative to the aircraft, and sea surface information is needed to reduce the depth measurements to mean sea level. A bread board model of this implementation has been tested with data from the NASA-AOL system (Byrnes and Fagin, 1978).

It is not possible to track heading error via the aircraft-to-surface slant range, since we are projecting to a quasi-flat surface. The only possibility for tracking heading error is via the grid technique, which will be discussed in the next section. Error analyses indicate that the grid technique for tracking heading error works only where the ocean bottom displays complexity; of course, this is where the capability is most needed.

The three main reasons why an optimal solution has been chosen are: (1) errors affecting position become more critical as the survey swath width gets wider; and (2) alignment between attitude sensor and laser become more subject to error because of the non-permanence of the installation in the intended helicopter; and (3) even with careful procedures, misalignment is still possible and could go undetected if a tracking capability is not included in the processing.

Alignment errors can originate from both mechanical and timing sources. Mechanical sources arise simply from physical alignment inaccuracy or coupling arrangement. Timing sources occur when data are recorded at different rates in groupings with a time tag and later interpolated and correlated. Errors from these sources are minimized when the processing is conducted in a closed form, and that is precisely how the optimal solution operates.

In a closed form solution, unmodeled error sources propagate unrealistic results with wave lengths which are inconsistent with the processing model. This is one way that optimal filter theory can be applied as an error analysis tool. The technique was applied to NASA-AOL data and was demonstrated to be a powerful analytic technique (Byrnes and Fagin,1978).

The main penalty one pays for the above type optimal solution is computer computation time. The load increases as the number of state vectors increase. It is anticipated that the optimal solution can be modeled as a six-vector problem. This size model entails the computer performance of approximately 150 multiplications, 150 additions, 150 substitutions, 5 sine executions, and 5 cosine executions for <u>each</u> slant range observation incorporated. Since one tape may hold about 1 hour of data, at a rate of 400 Hz, the number of slant ranges to be processed would amount to approximately 1,440,000. At this time, we do not know exactly what particular computer will be used for processing; some small computers do have computation times similar to the Univac 1108. Assuming 1108 execution times of 2.625 μsecs for multiplication, 1.875 μsecs for addition and substitution, and 60 μsecs for sine/cosine, a full data tape would require approximately 37 minutes of computer computation time.

The question of computer time will remain fuzzy until two basic decisions are reached; namely, what quality of new computer NAVOCEANO will purchase for their shipboard processing system, and the capability of the HALS on-board computer. The computers being considered by NAVOCEANO for shipboard installation will have hardware multiply/divide module as opposed to older type mini-computer where multipliation was accomplished via a series of software instructions. This means that the data can be processed at speeds similar to the Univac; or in the worst case, may require about 1 hour of CPU time. The specifics of the HALS on-board computer will not be available until the system is designed; however, preliminary sizing indicates that the HALS computer could be equal to or even exceed the NAVOCEANO selection. An ideal solution would be for the HALS computer to be configured in such a way that it could perform and post survey the main bulk of the number crunching, with the NAVOCEANO computer performing a limited number of functions, such as display and listing.

Assuming that the HALS system is completely dependent on the shipboard computer for all processing, one hour does not seem excessive, since one can assume that the shipboard computer will not be used at full capacity on a daily basis. The processing problem is further eased by indications that NAVOCEANO will maintain a backup computer to support onboard production processing. It is possible that we may end up with a choice of three computers capable of processing the HALS data. Bottlenecks could exist for short periods of time, but only when the HALS performed several consecutive missions in that short period of time. In normal operations it is expected that the HALS system could acquire the data and complete the processing before the soundboat could complete a day's work.

Some thought has been given to the idea of merely verifying that good data have been collected, and then completing the processing at the NAVOCEANO base plant. The flaw in this concept is that assurance of quality data and absence of holidays are required on-site before the NAVAIDS are moved, and, in many instances, the capacity for producing a nautical chart on the ship is required.

B. THE HALS DATA FILTER

A large percentage of data collected by the HALS system will be acquired from areas where the bottom is complex and the data integrity will be suspect, at least to the human eye. In an area where the bottom is complex, there is no simple way of determining if that lack of data integrity is simply a reflection of residual position error and uncompensated sea surface or if the observations have been contaminated by bit dropout, fish, turtles, grass, seaweed or even difficulties with bottom pulse placement because of changes in pulse shape.

A solution to this type of difficulty comes in the form of a filter; even soundboat data undergoes some filtering, at least by eyeball, before data are selected for charting. The situation with soundboat data is very much <u>unlike</u> the HALS problem, since the sounder records the depth of only the most shallow object within a small cone. The small cone provides a very narrow swath when compared to the anticipated HALS swath and is often considered as a profile. The HALS system provides such a wide swath that it must be considered two-dimensional, and therefore requires a two-dimensional filter.

A prototype two-dimensional filter is described in Fagin Associates (1977), but its implementation requires a large amount of computer time. The prototype filter deals with the filtering and the slant range processing all in one minimum variance solution. Development is underway to modify that solution to provide a production mode filter which will require less computer time. The desirable characteristics which will be incorporated into a two-dimensional HALS filter are as follows:

1. Deals with depth error and position error simultaneously.
2. Incorporates or rejects data on a statistical basis.
3. Insures that bottom slope is part of rejection criteria.
4. Deals statistically with redundancy.
5. Weights data in favor of shallowest depths.
6. Converts data into an equally spaced grid.
7. Defines end product quality.

The above items are all closely related, and, to a large extent, are actually tied together in the Optimal Laser Survey described in Fagin Associates (1977). The new algorithm being developed will incorporate those same items, but in a sub-optimal fashion. Reasons for identifying those characteristics are explained as follows.

Figure 2 shows a swath of data plotted under the aircraft. The density of data is such that many observations are plotted very close to one another--in fact, some are plotted one on top of the other. A closer look would show impossible gradients between adjacent points. The major portion of these data observations were well within specified limits of position and depth error. This points up the reason for dealing with depth error and position error simultaneously.

The ability to incorporate or reject data on a statistical basis involves a buildup of confidence as more data are incorporated into a specific survey area. The first observation seen by the filter program will be accepted and incorporated, but the confidence level (i.e., covariance matrix) will remain very low. As more observations are incorporated, the filter will become capable of predicting what the next observation should be, and knowing its own capability via the covariance matrix, will know how accurately it is able to predict that next observation. When the new observation exceeds the prediction by a predetermined amount, usually 2.5 or 3.0 Σ, the new observation is rejected. The pattern of rejections is used to determine suspect bottom structure. Normally rejections are expected to assume a random distribution, where rapidly rising coral heads or steep-sided channels exist, rejection occurs in a pattern. When a rejection pattern is detected, the suspect area should be reflown as a saturation survey. Where steep-sided channels are encountered and high accuracy is desired, the saturation survey should be conducted as precisely as possible (i.e., precise gyro alignments), and the data processing adjusted (i.e., reduced grid spacing and increased slope tolerance) to these specific needs.

Bottom slope rejection criteria come into play as soon as a sufficient amount of data are available for prediction. In the HALS system this occurs quite rapidly, since the scan system is such that just one sweep through 360^{o} provides some general slope information in all directions for a large area. Insight into the slope rejection technique can be derived from the scan pattern shown in Figure 2. At the right side of the data swath, the HALS sweep is encountering "new" survey area. Here the observation can be predicted only by slope values from behind the sweep; the confidence level is therefore low and most observations would be incorporated, but with low weighting factors. As the HALS sweep moves behind the aircraft, data ahead, behind, left and right have already been incorporated into the filter and used in the prediction. The confidence level is very high. In this case the new observation

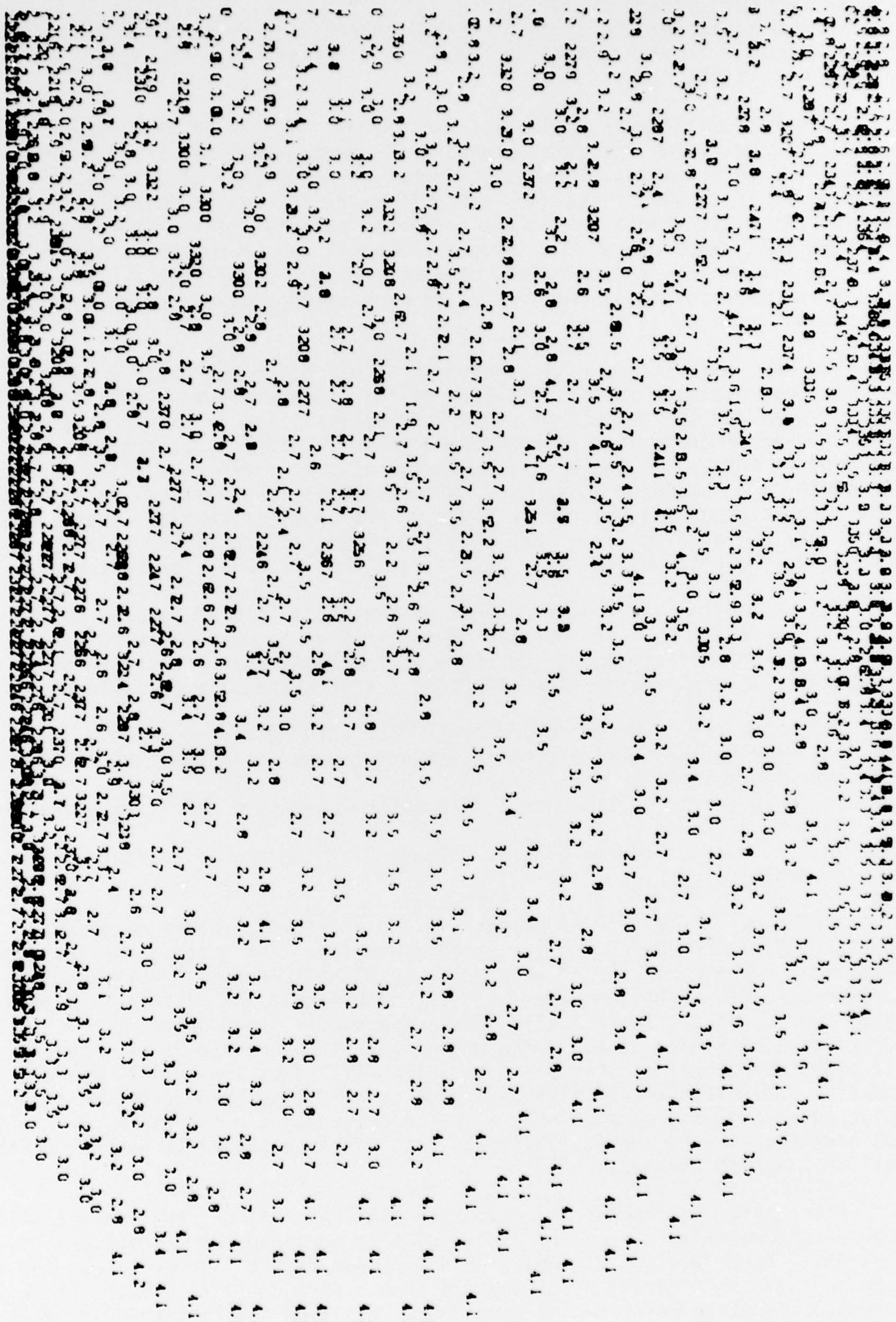

Figure 2. Data Swath

must meet more stringent requirements if the observation is to be acceptable. The confidence rises even higher after acceptance, since the new observation is tagged with a higher weight.

This discussion also applies to redundancy. It can be shown statistically that redundant measurements can be processed in such a way that results are of a much higher quality than any individual measurement. The density of data (i.e., redundancy) at the edges of the HALS swath (Fig. 2) is greater than in the center of the swath. At first glance this might appear as wasteful data. However, it should be realized that there are no data beyond the edges and therefore an absence of slope control for evaluating, rejecting or incorporating new observations. In effect, the scan pattern compensates for the lack of slope knowledge at the edges by redundant measurements.

The HALS data filter will be capable of weighting the observations in favor of the shoalest depths. The desirability of this characteristic is based on the primary purpose for the conduct of near-shore surveys, namely safety. As new observations are incorporated into the HALS filter, each observation is weighted by the covariance matrix; to the weighting factor will be added some value proportional to the depth being observed before the observation is incorporated. In this manner the end product (chart) is biased in favor of the shoalest depths. When the bias is done this way, it does not mean that only the shoalest observation in a given area is incorporated; the observation still must pass all other rejection criteria.

The HALS data filter will convert observations into an equally spaced grid representation of depths. The purpose of the grid is to make the data more sparse; there is no intent to interpolate for data at locations when there were no observations. Several reasons for selecting a grid system are as follows:

1. The grid is a good way to represent data already incorporated.
2. The grid can be modeled to maintain one-to-one correspondence with a covariance matrix.
3. The grid can be adjusted to follow bottom curvature merely by increasing density.
4. The end product can be plotted without plotting one data point over the top of another.

Accompanying the grid of depths will be a grid of quality designators (covariance matrix) which define end product quality. The quality designator will be a statistical quantity which reflects quantity of measurements, proximity of measurements, slope of bottom, and integrity of position and depth measurements actually incorporated. These quality designators will prove useful where we compare soundboat data with HALS data. Where a soundboat track crosses a HALS swath, we should expect agreement only to the accuracy specified by the quality designator. The quality designator should also be useful in selecting grid depths which actually get plotted--i.e., when we plot only a few depths, from a whole swath, on a 1 to 50,000 boat sheet. The quality designator will also be useful in describing the overall HALS survey accuracy.

After data are processed through the HALS data filter, the results will exist as a very long rectangular grid of depths with an accompanying grid of quality designators. There will be one whole grid for each flight line or a grid for each line segment if the aircraft track departs from a straight line. Each grid will have an origin designating latitude and longitude. Latitude and longitude for any specific depth will be relative to its position in the grid and the origin.

From the grid, the operator can select the shoalest depths and other depths for plotting on the smooth sheets. Data can be sent to the DMA library in this compact form, or each grid intersection can be tagged with latitude and longitude and sent to the library. The original tapes which were recorded on the aircraft could be recycled or saved and put into archives.

A question of legality arises with a grid, since the result of this process is, in reality, a minimum variance estimation of depth at the grid intersection rather than a direct observation of depth. Traditionally, direct depth observation, with specified horizontal and vertical accuracy variable with chart scale, is required where soundboat data are incorporated into a chart. Assuming that this requirement governs the use of HALS data, an additional data pass will be required. The additional data pass would search the original data tape for a direct observation which most closely matches the minimum variance estimate near the grid intersection and replace that estimate with a direct observation. This may appear somewhat facetious, but it can be done in a statistically sound manner and should satisfy the requirement.

C. NAVAID SMOOTHING

As indicated in previous sections, the HALS may be operated primarily with a medium range NAVAID system. The employment of a medium range NAVAID infers that the HALS will be required to operate at greater distances from the NAVAID transmitters. At these anticipated greater distances we can expect to encounter a higher standard deviation of position error, greater net bias, and more frequent lane jumps than would have been expected with a short range NAVAID. These greater position errors may be tolerable for some specific charting requirements, but they do tend to obstruct the effectiveness of the "HALS data filter," since position errors can overwhelm depth measurement error. The reduction in the effectiveness of the "HALS data filter" implies a reduction in the validity or integrity of HALS depth measurements, since redundant measurements may not be expected to agree. The implementation of any quality control algorithm must be based on the first assumption that data from the forward sweep must be in agreement with data from the laser backward sweep as the backward sweep overtakes that forward sweep because of the forward motion of the aircraft.

A visualization of the difficulty encountered from increased position error can be realized by considering a plot of position information. The plot represents the aircraft track - data points are plotted relative to the track; if the heading of the aircraft is identical to the track, no side slip ("crab" angle), then data plotted fore and aft of the aircraft will lie on the track.

If side slip does exist, we can still plot the points which fall on the track if that track is correct and we know true heading to the required accuracy. The difficulty is that as position deteriorates, the track deteriorates and data plotted relative to that deteriorated track cannot be expected to align correctly, fore and aft, with any degree of confidence--even when the geometry is solved with the correct true heading. What this amounts to is that alignment of data fore and aft is a function of side slip angle, and the error in side slip angle is a function of both track error and the true heading error. When the unknown error in slide slip angle exceeds two degrees, we may expect fore and aft data disagreements in direct proportion to the unknown angle and bottom slope. As the bottom slope approaches 5°, we can expect the HALS data filter to begin tracking the error in side slip, but only to the degree with which bottom slope remains constant. In areas where the bottom is complex and the slope changes direction rapidly, there appears to be little hope of unraveling the whole ball of wax via depth measurement alone.

Aircraft side slip is not the only difficulty which may be caused by position deterioration. Knowledge of aircraft speed deteriorates as well; even when we know the orientation track well, errors in speed would limit our ability to evaluate the data validity to some extent.

The above difficulties can be reduced by smoothing the NAVAID positions. The recommended type of smoothing differs from that which vendors supply with their equipment because it will not be applied in real time. A real time positioning process can use only past data, and therefore can perform only a filter process. A filter process is fine for operations where one is concerned only with where he is going; in charting work, we are concerned with where we have been. Smoothing can be accomplished best after a whole survey line is completed. An optimal smoothing process can be devised to use all data preceding and following a point of interest when determining each position estimate, i.e., if a survey line is one hour long, the whole hour's observations can be used for computing a smoothed estimate for a specific time. The data required for a smoothing solution are available only after the survey is completed. Optimally smoothed position estimates present a refined, statistically improved, continuous portrayal of where one has been.

The practical length of time over which a series of data should be smoothed is dependent on the correlation times of the state vectors associated with the model; the onboard aircraft systems determine the composition of that model. If the onboard system includes an airborne inertial system, the errors to be tracked would be the slowly varying drifts of that inertial system and the practical length of time over which a series of data could be smoothed would be lengthy. The employment of an inertial system and lengthy smoothing times are most practical where the time between independent position (NAVAID) observations is lengthy or when one is attempting to compensate for net bias by incorporating short range NAVAID observations or satellite Global Positioning System (GPS) data.

The techniques for smoothing position information associated with an inertial system are described by Byrnes and Fagin (1975). The modeling for the HALS smoothing process will be much less sophisticated than Byrnes and Fagin employed, but the techniques will be similar. Since an inertial system is not anticipated for the HALS development, the smoothing will be based simply on aircraft motion. The correlation times for this type model will be short relative to a model employing an inertial system. No state vectors associated with net bias will be employed, since no independent observations of net bias are anticipated. The smoothing model will be capable of (1) reducing the standard deviation of the random position errors and (2) detecting lane jumps.

The model for smoothing the HALS position information would normally require six state vectors. If one assumes latitude and longitude errors to be uncorrrelated, the major portion of the computations can be performed treating latitude and longitude independently. This independent treatment reduces the model to the computation equivalent to approximately three state vectors. Even with three state vectors, the computer time required to process a one-hour data tape would be intolerable if we were to compute a smoothed estimate of position for each 400 Hz HALS observation. The solution to the computer time problem is to compute smoothed position estimates at a rate of one per second and then interpolate for the 400 Hz rate. The implementation of the interpolation scheme reduces the computer load to the extent that the processing is bound primarily by input-output speed.

It should be apparent from the above general discussion that as position information deteriorates, the quality of depth information may deteriorate. This is basically true because we have taken advantage of redundancy (in the HALS filter grid) to improve the quality of the end product. The concept of depth measurement deterioration with position diverges considerably from traditional concepts where soundboats are employed for surveys. Soundboat measurements do not rely on redundancy and are therefore never affected by position error. It could be shown that end products from soundboat data could be improved via redundant observation, but that is not the purpose of this discussion. The purpose of the whole discussion on positioning has been to indicate that some degradation in end product (chart) quality can be expected when operating with a medium range NAVAID as opposed to a short range system.

IV. DATA DENSITY

The effectiveness of HALS for detecting and registering submerged rocks, pinnacles, sheared pilings or other relatively small objects that may be hazards to navigation becomes a real numbers game. The ability to detect a small target is a function of target size and the spatial distribution of the laser spots. Detecting a target once would never be enough to satisfy any reasonable confidence level. Detecting a target ten times in the same location does instill some confidence. A sheared piling type of target with one square foot of surface area would require 10 laser pulses for every square foot of area being surveyed. Using a laser having a pulse repetition rate of 400 per second, we could survey 40 square feet per second. If the swath is adjusted to 40 feet coverage, the forward speed of the HALS platform would be limited to one foot per second. This coverage is very low and could be done more effectively by ship using a wire drag or side-scan sonar.

Assuming a target area of 100 square feet yields numbers that are more in line with airborne sensors. For a hit rate of 10 per target in keeping with our confidence level, only one pulse per every 10 square feet is required. Using a 400 Hz laser pulse repetition rate, 4000 square feet per second can be covered. A 40 foot swath would mean that the survey could progress at 100 feet per second. For a 100 square foot target this survey rate of 4000 square feet per second translates into 14,400,000 square feet of coverage per one HALS mission hour or 0.4 square miles per mission, a rate that is competitive with other techniques for registering medium-sized navigation hazards. The hit rate of 10 per target as used above is a rather arbitrary number, but it does have relevancy when considering some soundboat operations. An equivalency can be attempted by assuming that a soundboat is equipped with the Raytheon 723-M, operating at the meters X 1 scale, pinging at 10 Hz. At launch speed of 17 knots the system pings every 2.9 feet. For a 20 foot depth and a 45° cone width, the system covers a circular area with a diameter of approximately 16.5 feet. Since the launch is advancing at 2.9 feet per ping, the circular areas overlap and any target within that swath would be sensed at least 5 times as the launch advances. Obviously, at lower speeds, a target would be sensed more often; in more shallow water, assuming the same 17 knot speed, less often.

Sensing a target five times via soundboats cannot be directly equivalenced to the HALS, since the energy from a sounder covers the whole area within the 45° cone and reflects from the nearest target, whereas the HALS illuminates a proportional area, but responds to all the return energy within the receiver field of view. This does, however, point up the need for more dense sampling by HALS to approach equivalence with a sounder; thus, the arbitrary hit rate of 10 per target for the HALS.

The more likely application of HALS is for the detection of a shoal area where the bottom becomes gradually shallow. In this case the target area exceeds 2500 square feet and the survey rate becomes more realistic. With the aircraft at 500 feet altitude and the scan set to 36° off nadir, a 700 foot swath could be surveyed at 70 knots, providing an average target hit rate of 12.6 per 2500 square foot target.

The 2500 square foot target ascribed to a shoal area is to be taken only as an estimate; experience will enventually dictate swath width and data density. In actual practice, it may become desirable to perform a reconnaissance mission to determine data density; however, it should be apparent that as an attempt is made to define smaller objects via HALS, the trade-off in rate of coverage proceeds to the impractical in cases of very small targets.

Assuming that the primary application for HALS is the charting of shoal areas and not the detection of small hazards, a question still arises concerning data density vs. chart scale. The answer to that question is simply that no matter what chart scale, the purpose of the survey is to insure safety of navigation. To insure safety of navigation the shoalest depth must be recorded no matter which chart scale is being used. In order to determine the shoalest depth the system must be able to detect all shoals in the area. If it is assumed that the target area for the shoals is 2500 square feet, and a reasonably high level of detection confidence is desired, then the density relative to the target size must be set and the chart scale has little significance. It is, therefore, expected that aircraft operations, altitude, speed, swath width, and essentially data density will be quite similar for chart scales ranging from 1:5000 to 1:50,000. Only when it is determined that finer structures (i.e., smaller targets) are to be observed would the data density be varied. This would be more of a function of bottom than a function of chart scale. The intimation of a requirement for a 1:5000 scale chart as opposed to a 1:50,000 scale chart is that finer structure should be observed. However, what it really means, especially in the case of HALS data, is that more data are plotted.

Chart scale does become significant in determining the quantity of data points that actually get plotted from the massive array of data collected. Figure 3 shows a typical data swath overlaid by a grid with 100 foot spacing. The grid represents the number of data points which could be plotted on a 1:5000 scale chart. The average ratio of data observations collected to the number of points which can be plotted at this scale is about fifty to one. If a plot of this same data is made on 1:50,000 scale chart, twice that amount of data would be processed into just <u>one</u> plot point. In this second case, the ratio of data observations collected to the number of points which can be plotted is about 1872 to one. It may appear absurd to collect a massive amount of data and end up plotting so little, but it must be remembered that a massive amount of data is required for detection rather than plotting. It should be apparent that data collected by HALS via 1:50,000 charting requirements would have density suitable for production of 1:5000 scale charts; the only thing lacking may be position accuracy which is dependent on the specific NAVAID employed.

In his doctoral dissertation, Davis (1974) indicates that data density should be governed by the amount of bottom variation encountered in a specific small area, which he calls provinces, and the amount of sample error which one will tolerate. His dissertation is directed toward selection of survey track spacing, but it is applicable to the question at hand. The provinces are established via reconnaissance data which are processed through a high-pass filter. The filtered data is then divided into provinces of homogeneous segments. A one-dimensional Fourier transform is applied to the provinces, with the resulting spectral estimates being processed through some additional equations to obtain estimates of sample error as a function

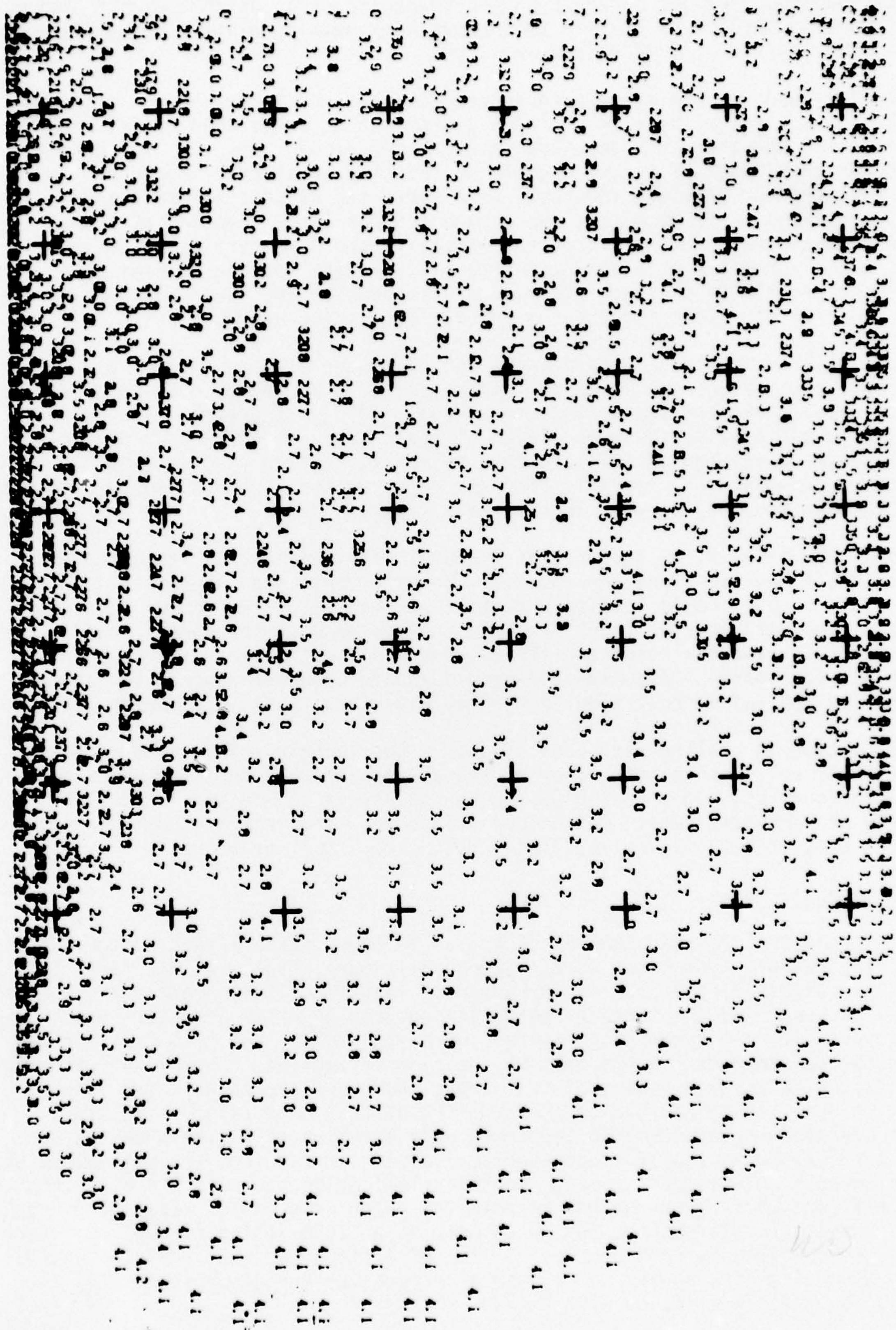

Figure 3. Plot Points at 1:5000 Scale

of sample spacing. For our purposes we can equate spectral estimates with target size. A Fortran version of this technique has been developed for the Hydrographic Surveying and Charting (HYSURCH) program.

Data for input to the above program are soundings collected at 5 m intervals along track. Equivalent data from a HALS system can be envisioned by assuming a profile constructed from data acquired down the center of Figure 3. The density of data through the center of Figure 3 would be relative to aircraft speed and swath width. Assuming our previous 700 foot swath width and 70 knot aircraft speed, the aircraft is advancing at 36 meters per second and the laser scanning at 5 Hz. Since the scan passes both fore and aft of the aircraft, the 5 Hz rate is essentially doubled, hence a profile with approximately a 3.6 m data spacing is available. When a more dense profile is desired, the data at the edge of the swath could be utilized, thereby even further exceeding the 5 m intervals used for HYSURCH.

If we wish to constrict data density vs. sample error more in line with the HYSURCH analysis, it becomes immediately apparent that an increase in speed can be tolerated (i.e., 700 foot swath, 100 knot speed, 400 Hz data rate). The 100 knot speed exceeds our previous assumed (70 knot) speed, but is a good beginning density for an unknown survey area. The data density for succeeding missions could then be altered to accommodate any specific charting requirements as the survey progresses by processing data profiles as described in Davis (1974).

One of the interesting features of the HALS scan pattern, as indicated above, is the fact that a profile along the edge is much more dense than a profile down the middle. This feature could lead to a more simplified determination of data density. If a one-dimensional Fourier transform were applied on both the center profile and the edge profile, and the results differed, one would automatically know that the sampling was too sparse. Assuming adequate on-board computer power, this concept could even be applied in real-time to control data density as it is being acquired.

One caution in dealing with data density - the technique described in Davis (1974) deals only with sample error on the assumption that the data being processed are true and correct. In a real HALS survey the errors can be minimized by proper processing of redundant data. Redundancy transposes into increased data density; therefore, data density may not be dictated by sampling error alone.

V. TEST RESULTS

Tests conducted via the NASA-AOL system at Wallops Island Flight Center establish the fact that a HALS system can work. Some preliminary results of AOL field tests showing this workability appear in Appendix A. Results of tests concerning aircraft altitude, attitude and sea surface (potential sources of error affecting position and depth measurement) are reported in Byrnes and Fagin (1978); the potential for tracking the sea surface via the optimal solution is implied. Experience with optimal filter techniques indicates that where the model tracks half the vectors well, it is most likely capable of tracking the others. The evidence is still somewhat sparse--AOL data used in the tests were acquired at a time when the sea surface was very calm; a plot of sea surface values derived from the optimal solution also indicated a smooth sea surface. Profiles indicating how well the algorithm tracked altitude were not presented because the pulse compression radar altimeter on board the NASA aircraft was not set up to work at a 1500 foot altitude; therefore, no data were obtained for comparison. A plot of altitude derived from the optimal tracking algorithm did, however, indicate a reasonable average altitude and reasonable changes in altitude with time.

Prior to the NASA-AOL tests, a "model for Optimal Laser Surveying" (Fagin Associates, 1977) was developed and exercised via computer simulations in order to determine system trade-off and to anticipate results which might be obtainable from AOL. The Optimal Laser Surveying model was designed in such a way as to force all errors, position-related or depth-related, to become observable in depth measurements only. This is a rather unique approach in survey analysis, but is readily accomplished by recognizing that any position error can be transferred to depth measurement error if the slope of the bottom is known. In the simulation we constructed a precisely known bottom with slopes and "target areas" within the detection capabilities of HALS. From the precisely known bottom, a grid of data was established to serve as the datum through which the results of varying any of the system error sources would be compared.

Simulated slant range observations were acquired by "flying" the elliptical pattern over the known "targets" at a given altitude and computing slant range distances from aircraft to the sea surface and the sea surface to the bottom. Prior to computing the slant range distances, the "aircraft" positioning, altitude, attitude, and heading were contaminated with appropriate errors to confuse the positioning--i.e., the simulated depth measurement is a correct measurement, it's just that its location is not very well known. After the slant ranges are computed, they are further contaminated by sea surface and slant range measurement error.

With the simulated observations compiled and stored on tape, the processing begins. The program reads simulated data from a HALS tape. The positioning, altitude, attitude and heading are assumed to be correct in the same way that real data would be assumed to be correct--even though it is known that in both cases we do have errors.

The data are now processed via the optimal laser survey processing program into minimum variance grid estimates. After the process is complete the estimated grid is compared to the true grid, and an RMS of residuals is now available to indicate improvements or deterioration of the whole survey resulting from varying individual system error sources.

The initial modeling was set to reflect a somewhat pessimistic system as follows:

Variable	1 Σ Error	Correlation Time
Aircraft Positioning	2.5 meters	1 second
Aircraft Altitude	10.0 meters	10 second
Aircraft Heading	3.0 degrees	2 seconds
Aircraft Pitch	3.0 degrees	2 seconds
Aircraft Roll	3.0 degrees	5 seconds
Wave Height	0.33 meter	1/400 second
Slant Range/Surface	0.33 meter	1/400 second
Slant Range/Bottom	0.33 meter	1/400 second

As could be expected, when an error analysis is designed in a manner in which all error is forced to become observable in depth only, the bottom slope becomes a dominant factor, since all position error translates into depth. The initial tests were conducted assuming a maximum slope of 5° (much greater than any slope encountered in the AOL tests). Even with this pessimistic system and large bottom slope, results from the simulation indicated that the bottom could be charted within 0.43 m RMS of the datum.

A more optimistic model was simulated to represent the anticipated HALS system. For this model the heading error was changed to 1^{o}, pitch and roll to 0.2^{o} and slant range measurement errors to 0.1^{o} m; all other variables remained constant including bottom slope. The results for this experiment indicated that the bottom could be charted to within 0.20 m RMS of the datum.

Other tests conducted in this manner provide insight as to what can be expected in real operations. Demonstration of the effects of specific items of interest was accomplished by varying only selected state vectors. One such test demonstrates the effect of surface waves. The experiment was executed with waves modeled with one foot RMS amplitudes; the test was then repeated using 3 foot RMS amplitudes for the waves--results indicate that a 0.5 foot RMS error increase would be experienced when preparing a chart from data where 3 foot RMS waves are encountered.

Tests on data density were simulated. The results of one set of tests indicate that surveying an area with a 100 Hz system as opposed to surveying the same area at a 400 Hz pulse repetition rate almost doubles the RMS error. Another test, where the data density was doubled by cutting aircraft speed in half and "flying" a longer mission, provided only a 20% improvement. These results indicate that data density does indeed have an influence on the end product. Also, it appears that increasing the data density further would provide diminishing rewards. The second test described here would be more indicative of data density which would be associated with the HALS system, since it is intended for installation in a helicopter which would travel at half the speed of the NASA aircraft. A conclusion which can be drawn from the above is for a helicopter flying at 70 knots, surveying a swath 700 feet wide, the 400 Hz pulse repetition rate is an appropriate selection.

Results of other tests were mainly as expected. The results improved when the bottom slope and bottom complexity were reduced. The same held true when the roll and pitch quality improved. Maintaining swath width while varying altitude and scan angle to maintain a specified swath width were found to have no discernable impact in terms of the resultant RMS of grid residuals. The swath width test, however, does not take into account the possible pulse "stretching" of the bottom pulse and the subsequent possibility for misplacing that pulse as shape changes because of the effective field-of-view increase with altitude.

Tests where the quality of the slant range measurements were modeled differently--i.e., slant range from aircraft to sea surface 0.1 m RMS--slant range from sea surface to bottom 0.6 m RMS, indicate that the system is more directly sensitive to the slant depth measurement than to the slant altitude measurement. The interesting part of the exercise is that even though the system maintained good control of the surface waves, error was still able to propagate via the heading, which is the most uncontrollable state vector in the model. Even with the 0.6 m RMS error modeled for the slant depth and accompanying errors in state vectors as described in our optimistic model, the RMS residual for this test was 0.32 m.

The difficulty which was experienced with heading was also apparent in other tests. The model for optimal laser surveying was capable of tracking heading-induced error only when the bottom was very complex. To determine model capability for tracking heading error, several tests were exercised wherein a known 2^{o} RMS heading error was simulated for each test; bottom slope was then varied in steps from 2^{o} to 5^{o}. Results indicate that heading error is difficult to track with bottom slopes less than 5^{o}. This can be explained by considering the geometry of the situation--considering the worst-case condition where the half-width of the swath is 350 feet, a 2^{o} heading error causes a maximum displacement of 24 feet in position. This 24 foot displacement in position would cause a 2 foot apparent depth observation error where the bottom slope was 5°; where bottom slope is 2°, the same displacement causes only 0.8 foot apparent depth error. Since other state vectors can readily accommodate the 0.8 foot in the error propagation model, there is little error left for heading to be sensitive to in the case of a 2° slope. As the bottom slope approaches 5°, the larger apparent observation error saturates other state vectors in the error propagation model and the model becomes sensitive to heading error. To improve the situation and cause the model to become sensitive more quickly to heading error, other state vectors within the model would require improvement; but, since the model is in actuality already optimistically descriptive of the anticipated HALS system hardware capabilities, the likelihood of improvement in the required state vectors is remote. The alternative is to begin with a good heading reference, bound the drift errors via external calibration procedures, reduce error allocation attributable to heading and improve the overall model.

VI. ENVIRONMENTAL CONSIDERATIONS

The performance of the HALS in any particular survey area will be limited by in situ water conditions, i.e., average normal water conditions, as well as current disturbances of the water caused by the prevailing weather. Little can be done about the in situ conditions, but current weather conditions do change and to some extent can even be predicted. The anticipated employment of the HALS as a complementary system to the present NAVOCEANO near-shore surveys does, however, preclude individualized planning for seasonally advantageous utilization and somewhat narrows the time window at the survey site. The intended use of the system must dovetail with the sound boat utilization and NAVAIDS deployment. In many instances, sea-state conditions will be such that sound boats will be able to conduct business as usual when the HALS operations are delayed while waiting for the water to clear. This will be generally true for a few days following a storm, since sediment particles will be stirred up and require some time to settle. The best indication of whether the HALS can perform, short of installing the system and trying it, is the human eyeball; if the bottom can be seen, the HALS should be able to perform very well.

The quality of the water column is expected to have the largest influence on the usefulness of HALS; in some areas where laser penetration is limited to less than one foot, using the HALS would not be practical. The same would be true where white water exists or when rain or fog are encountered. When the sea surface is perfectly flat, laser surface returns will not be available and the system will be severely limited. When direct sunlight reflects from the sea surface into the receiver the signal-to-noise ratio is seriously affected.

All the above points to the fact that the operator will have to be the judge as to when and where the HALS is employed. He will need to be able to anticipate if conditions are tending to improve or deteriorate and pick a time when the best probability exists for a successful mission. A major advantage for the operator is that a mission can be accomplished in less than two hours.

The anticipated operational window for HALS is at dawn or dusk (low sun angle, indirect sunlight) with winds 2-20 knots (2 knot minimum for creation of capillary waves necessary for surface reflection, 20 knot maximum white water limit) and sea waves below three feet peak-to-trough (higher waves may be tolerable, assuming a good wave tracking algorithm, but higher waves may mean more suspended matter in the water column).

The operator for the HALS system will be a trained, journeyman-level scientist or engineer. Once the operator decides that the environment provides a good possibility for a successful HALS mission, he will proceed with operations as described in the operating synopsis. His normal duties while on a mission will include instructing the computer which controls the HALS and changing magnetic tapes when required. Because of the short duration of the missions, the operator will be required to change tapes no more than once per mission. The primary function of the operator will be to observe the system performance via a digital display unit and an oscilloscope. The operator will have the authority to abort the mission when it appears that useful information is not being acquired.

The success of a mission will depend on the quality and quantity of the bottom returns received. Signal-to-noise ratios available via the digital display unit, and laser return waveforms available via the oscilloscope, will aid the operator in his evaluation of quality. The quantity of data required for a successful mission relates to data density as discussed in a previous section: depending on bottom variability, swath width, and accuracy requirements, some specific percentage of laser returns will be necessary and the operator will be required to obtain a "feel" for what the percentage must be.

In instances where data distribution is uneven, i.e., where the bottom slopes rapidly transverse to the aircraft track, the data density may be adequate for defining part of the swath. In these instances the operator can display signal-to-noise ratios relative to laser azimuth and evaluate the presence of that condition. Where data distribution is uneven, the operator may choose not to abort a mission. On missions where quality laser returns are received randomly and where the quantity of data does not meet chart requirements, the operator may assume that those returns are from the shoalest areas and the data could be used as reconnaissance type data for purposes of estimating soundboat safety.

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APPENDIX A

LASER BATHYMETRY FOR NEAR-SHORE CHARTING APPLICATIONS (PRELIMINARY FIELD TEST RESULTS)

LASER BATHYMETRY FOR NEAR-SHORE CHARTING APPLICATION
(PRELIMINARY FIELD TEST RESULTS)

Gary C. Guenther
Lowell R. Goodman
David B. Enabnit
NOAA/National Ocean Survey
EDL, C61
Rockville, Maryland 20852

Robert N. Swift
Robert W.L. Thomas
EG&G/WASC
6801 Kenilworth Avenue
Riverdale, Maryland 20840

Abstract

An airborne lidar* system has been extensively flight tested to study the operational feasibility of using a scanning, rapidly pulsed laser beam, projected into water from a fixed wing aircraft, for near-shore hydrographic applications. Field test results for vertical accuracy, environmental constraints, and effects of system parameters are discussed. Detailed utilization studies indicate that such a system should yield significantly reduced cost as well as increased volume of near-shore bathymetric data for charting purposes.

1. Introduction

During the past ten years, a number of increasingly sophisticated airborne laser ranging (lidar) devices have been tested to determine technical feasibility for hydrographic and other oceanographic applications (Ref. 1). In 1974, a development program for a versatile airborne laser and data acquisition system, to be sponsored by the NASA Advanced Applications Flight Experiment (AAFE) program, was proposed jointly by NASA/Wallops Flight Center and AVCO Everett Research Laboratory, Inc. The purpose of this collaboration was to produce and demonstrate, for a select community of potential users, a state of the art system utilizing NASA's expertise in space-age technology. Requirements, specifications, evaluation procedures, and applications for this "Airborne Oceanographic Lidar" (AOL) system were solicited and established through a series of meetings with interested parties (Refs. 2-5). The system evolved with two major and separate modes of operation: bathymetric lidar, and fluorosensing.

Preliminary shakedown and experimentation with the instrument in the bathymetric mode has been sponsored by NOAA/National Ocean Survey (NOS) and the Defense Mapping Agency (DMA), and conducted jointly by NASA and NOS. In this paper we shall discuss the results of the NOS test program (Ref. 6).

* light detection and ranging: the equivalent of "radar," but at optical frequencies.

Near-shore bathymetric measurements are presently accomplished by NOS primarily with narrow-beam acoustic (sonar) equipment mounted in small boats which work at relatively low speeds. An airborne laser bathymetric system has the potential to provide a higher quality product with more timely and less costly (Refs. 7 and 8) results in critical coastal and inland waters. It also permits new or improved services and shows great promise as a member of the hydrographic team. The objectives of the Laser Hydrography Development Project within NOS are to determine the capability of an optimized airborne laser system to meet or exceed NOS near-shore vertical accuracy requirements within a bounding set of system variables and environmental parameters; to perform preliminary design work on a realizable, NOS operations oriented system; to assess its cost effectiveness under "typical" operational conditions; and to investigate any potential outstanding problem areas which may develop. Flight testing of the AOL was primarily dedicated to the first of these, while also acting as a valuable input to the second.

2. AOL System Description

The Airborne Oceanographic Lidar (AOL) system, (Ref. 9) designed and built by the AVCO Everett Research Laboratory, Inc. under NASA contract, is installed in the NASA/Wallops Flight Center C-54 aircraft. An open hatch is used to pass transmitted and received energy to and from a large scanning mirror which is mounted between the floor and exterior skin of the aircraft. Water depths are determined for each laser pulse by measuring the time of flight difference between that portion of the pulse reflected back to the receiver from the water's surface and that reflected by the underwater "bottom" topography.

The AOL bathymetric configuration includes the following:

- an AVCO C-5000 gas (neon/nitrogen) laser with an unstable resonator (to improve beam divergence), an adjustable beam expander (for control), and an optional polarizer;

- a 56 cm scanner mirror with drive motor and 14-bit angle encoder;
- a 30.5 cm diameter Cassegranian f/4 telescope with adjustable field stop and baffles (0-20 milliradian field of view) and an optional polarizer;
- a narrow band (4Å) interference filter to suppress ambient background;
- a photomultiplier tube (PMT) detector with appropriate electronics;
- 40 charge digitizers (A/D converters);
- CAMAC interface;
- a computer controlled data acquisition, processing, display, and recording subsystem; and
- appropriate power and control provisions.

The laser wavelength of 5401Å (green) is near the minimum of the Jerlov (Ref. 10) curves of diffuse attenuation coefficient for coastal water types. The laser output power is typically 2 kilowatts (peak), while approximately 500 watts (peak) exits the aircraft in the primary beam. Divergence is variable from 0-20 milliradians, and maximum pulse repetition rate is 400 Hz.

The scanner is a nutating design whose mirror normal is offset slightly from the axis of rotation. The resulting pattern on the earth's surface is a tightly interlocked series of pseudo-ellipses (actually slightly "egg"-shaped) which provides relatively uniform areal coverage. The scanner can be operated either at a 5 Hz rotation rate or locked in a fixed position for non-scanning (fixed off-nadir angle) data acquisition. The nominal angle of the output beam with respect to the nadir is adjustable in 5° increments between 0° and 15° maximum deflection (this angle varies slightly during scanner rotation).

An altitude intervalometer, operating in conjunction with a surface return detector, triggers the electronics upon detection of the surface return and permits digitization of just the event data—automatically, independent of aircraft altitude. Delay lines are used to permit digitization of the surface return, as well as the bottom return, in the same output vector. (This feature is extremely important, as it allows use of the surface return shape and location for subsequent analysis.) The altitude data is also utilized to facilitate the removal of wave height variations from the depth calculations; this permits correction of the depths to mean sea level.

The 40 charge digitizers are gated sequentially at 2.5 ns intervals to provide 100 ns (or approximately 10 meters) of usable depth range. The digitized signals are transmitted through the CAMAC interface to a Hewlett-Packard 21 MX minicomputer with disk and tape storage and CRT display capability.

Aircraft attitude and rough positional data are supplied to the computer from a Litton LTN-51 Inertial Navigation System (INS). A Universal Time Code Translator interfaced with the system provides precise "real time of day" for each laser pulse. The entire system (electronics, laser, optics, and computer for both bathymetry and fluorosensing modes) weighs 2100 pounds and fits comfortably in a small section of the C-54 cabin.

3. AOL Bathymetric Field Test Program

Goals:

The goals of the NOS flight test program with the AOL system are to: validate the overall feasibility of a bathymetric lidar system to provide high quality data under typical operations-oriented circumstances; determine vertical error under a bounding range of system variables and environmental parameters and correlate error contributions with sources; quantify system and environmental usage constraints to establish the operational "window"; and model major contributions in a return signal strength equation to provide a sound basis for extrapolation of these results to the design specifications of an NOS prototype bathymetric lidar system.

Site Selection:

Site selection for the AOL field tests was based on the following criteria: depths must range between one and ten meters; a combination of both flat and relatively high relief topography is preferred; radar tracking of the aircraft is imperative due to poor performance of the LTN-51; the sites must be logistically easy to reach by both aircraft and ground support vessels; the area must have suitable tide "control"; typical water clarities must be appropriate to permit penetration to the bottom over sufficiently long portions of a flightline; and adequate meteorological support should be available 24 hours in advance for daily mission go/no-go decisions.

Two test sites meeting these requirements were selected (Ref. 11): one in the Atlantic Ocean over Winter Quarter Shoal (several miles offshore from Assateague Island), and one in Chesapeake Bay -- Tangier Sound between Jane's Island and Smith Island. These dissimilar sites provided the opportunity to investigate the effects of diversity in water clarity, depth, wind, and surface wave structure. The probability of successful missions in the Wallops Island vicinity based on precipitation, fog, and wind speed data from historical records was calculated and found to be acceptable. (Refs. 11 and 12)

Supporting Data:

A wide variety of ancillary supporting data was required for the flight tests in order to permit quantitative description of the system performance and the environmental restrictions on the operational window. The performance of the AOL is limited primarily by the product of water depth and optical attenuation coefficient. The latter is, for a given location and season, modulated temporally by wind, waveheight, precipitation, and currents; also affecting performance are such things as bottom reflectivity and solar illumination. These parameters interact with system variables such as receiver field-of-view, altitude, scanner angle, and beam divergence to yield a highly complex set of interactions which must be unraveled to permit the quantization of specific effects. Adequate testing of the AOL thus depended on the quality and quantity of ground data specifically tailored to meet needs. Primary support data acquired in conjunction with the flight tests include vertical control, horizontal control, water clarity, sea surface conditions, meteorology, and bottom reflectivity.

Vertical control consists of bathymetry and tide control. A bathymetric survey of the Tangier Sound flightline was conducted by an NOS vessel from the Atlantic Marine Center utilizing standard, automated, acoustic techniques. Horizontal control for this survey was a line-of-sight, high frequency electronic positioning system with ground stations. Tide control was furnished by three continuously recording NOS tide gages at appropriate locations.

Navigation and positioning of the aircraft were accomplished with the tracking radar and plot-board capabilities available at NASA/Wallops Flight Center. Radar data are smoothed with a Kalman filter program to provide the highest possible accuracy. Radar data are merged with AOL data offline during processing.

Water clarity measurements were made throughout the water column with a narrow beam transmissometer and were backed up with Secchi disk readings. (A well correlated linear regression of beam attenuation coefficient (α) against inverse Secchi depth was noted. This lends credence to both sets of readings.) Measurements were made in the vicinity of the flightline before, during, and after overflights. Attempts to measure diffuse attenuation coefficients (K) were foiled, with few exceptions, by baulky equipment. The observed relationship between and K, based on a very small data set, is not inconsistent with the Shannon (Ref. 13) equation ($K \cong \alpha/5$).

Winds were measured at the Wallops Island National Weather Service at several levels. Wind, waves, and visibility were measured subjectively from vessels at the flightline.

Bottom reflectivities in green and blue wavelengths were measured with a laboratory reflectometer. Grab samples were transferred in sealed plastic bags. Various handling and sample preparation techniques were investigated and yielded essentially identical results.

The support data was obtained as near to the time of overflights as possible. A total of over one hundred vessel "sorties" or "cruises" were mounted in support of the program. Cruise data was coded directly into an 80-column format and punched onto computer cards for inclusion in a "sea-truth" data base.

Test Description:

"Independent" variables and parameters chosen for investigation during the test phase are: water depth, water clarity, wind speed/wave height, solar illumination, bottom character, aircraft altitude, scanner off-nadir angle, receiver field of view, transmitter beam divergence, and receiver polarization. "Dependent" variables studied for effects of the above are accuracy (precision and bias), repeatability, hit probabilities, extinction coefficients, system attenuation coefficients, minimum resolvable depth, surface return signal strengths, bottom return signal strengths, noise levels, and detection algorithms. Data for these relationships was obtained within a four phase program. The data base for each mission includes a mission plan, the AOL system output tape(s), a digitized flight log of equipment settings and notes, a digitized ground data log, filtered radar tracking tapes, ground calibration data, a list of tape and data file numbers, a debriefing report, measured tide correctors, and sometimes ancillary materials such as footprint camera films, scope photos, and video tape of the monitor.

In 1977, 18 missions were flown with a total of 161 separate passes for an estimated total distance of 1000 linear nautical miles and 400 minutes of recorded data comprised of five million soundings. Aircraft speed was maintained at approximately 150 knots with altitudes ranging from 150 to 600 meters. Missions were flown in river, bay, and ocean waters, in hot and cold weather, clear and cloudy, night and day, for winds from 0 to 15 knots, with and without capillary waves, in water clarities with narrow beam attenuation coefficients varying from less than $1m^{-1}$ to greater than $4m^{-1}$, and with water depths from 0 to over 10 m.

Data Processing:

The tremendous volume of data acquired on even a single pass causes computer analysis to be mandatory. A wide variety of programs on a number of computers have been developed for data verification, reduction, display, analysis, and troubleshooting. The primary analytic tool for AOL data analysis is a sophisticated multi-function program called the "Processor." (Ref. 14) This program is extremely versatile because it is based on a freeform "keyword" input procedure with liberal defaults. Desired functions or procedures are easily activated and quantified by the inclusion of a single card in the setup deck. Briefly, the Processor unpacks and interpolates the asynchronous system data tape, identifies surface and bottom returns and quantifies their location and amplitude under control of a highly parameterized tracking algorithm, performs wave height correction, prints and plots altitudes, depths, waveforms, statistics, and other requested information, and supplies regressions and correlation values for all combinations of eleven specially selected parameters. An additional program is being developed to compare airborne lidar soundings with corresponding launch acoustic soundings and regress differences against a given parameter set.

4. Results

Preliminary:

Return waveforms from the initial flight tests were badly contaminated with electronic ringing and other spurious but repeatable noise sources whose amplitudes were greater than those of the desired bottom returns. To suppress this noise, a technique was developed which subtracts the system response to a surface return in deep water (with no possible bottom return) from the waveforms with bottom returns to yield a "residual" waveform in which only the bottom return pulse (and any uncorrected noise) appears. This subtraction is parameterized on surface return amplitude which drives the system response. Excellent resolution of bottom returns was achieved for even very weak returns approaching the digitization limit of the system (approximately 50 nanowatts at the scanner). An added benefit of this technique is the resultant subtraction of the surface return (and average solar noise and volume backscatter signal as well) which permits resolution of bottom returns at very shallow depths where they might otherwise be masked. Processor output results indicate bottom resolution to as shallow as approximately 30 cm.

Engineering:

Dominant environmental noise sources for a lidar bathymetric system are solar background reflection in daylight and volume backscattering of the laser pulse in the water column at night. A narrow-band interference filter centered on the laser wavelength reduces solar background level by a large factor. AC-coupling in the electronics further reduces this noise source. Volume backscatter has not been particularly evident in the relatively murky waters used for AOL testing because it occurs very close to the surface return, and because the deep water subtraction technique effectively removes it.

Bottom returns as low as 100 nanowatts can be tracked successfully. Surface returns range from ten to several hundred times larger. Probability of a successful surface return under most circumstances approaches 100% rapidly as the mean surface return signal strength reaches several times the trigger threshold. Typically for the AOL this occurs at about 2.5 microwatts optical power into the scanner. A glassy or mirror-like water surface during totally calm wind conditions causes the surface return probability to decrease while the dynamic range of amplitudes and overall mean amplitude increase. Operation under these conditions would not be recommended.

Penetration capability is probably the most important performance parameter for a laser bathymetric system next to accuracy. The maximum penetration depth, in general, is dependent on a large number of variables and parameters including laser power, altitude, water clarity, bottom reflectivity, off-nadir angle, receiver aperture, receiver field of view, receiver sensitivity, noise sources, and many more (Ref. 9); but for a given (appropriately designed and operated) system, the ultimate concern is water clarity. The reduction in bottom return signal strength with increasing depth can be described by the expression:

$$SSB \sim e^{-2kD}$$

where

SSB = bottom signal strength,

D = depth, and

k = "system" attenuation coefficient as defined by this expression.

The coefficient, k, has no particular theoretical basis, but simply provides a straightforward empirical parameter for describing system performance.

It has been established (Ref. 15) that for a sufficiently large receiver field of view, the value of "k" somewhat coincidentally approaches very close to the value of depth averaged diffuse attenuation coefficient ($\bar{K}$) for the water in question. Because of this fact, the product of $\bar{K}$ and the depth beyond which successful returns cannot be detected (D_{max}) is commonly referred to as the "extinction coefficient" ($\bar{K}\,D_{max}$); and penetration capability is frequently reported in terms of this unitless parameter. In addition, because an apparently linear relationship ($\alpha \cong 5K$) (Ref. 13) exists between diffuse attenuation coefficient (K) and beam attenuation coefficient (α) for water clarities of interest in coastal waters, extinction coefficients may also be reported in terms of αD_{max}. (AOL results will take this form because most cruise data is for α rather than K).

Calculation of "k" for the AOL (from the slope of $\ln$ SSB vs. D curves) resulted in values generally consistent with K. Maximum extinction coefficients observed in processed AOL data are $\alpha D_{max} = 12$ during the day and $\alpha D_{max} = 15$ at night! The latter was accomplished in December off Janes' Island with $\bar{\alpha} = 2.75m^{-1}$ and $D_{max} = 5.5m$. These results, considered to be excitingly high for such a low power laser, were defined at the maximum extent of high quality data, where hit probabilities remain in excess of 90% and precision (pulse to pulse agreement) remains no worse than 15-20 cm. Because of the sophisticated processing techniques applied to the raw signals, the loss of soundings at extinction tends to occur quite abruptly at bottom return signal strengths not greatly in excess of the minimum hardware digitization level. Projecting these results to a higher laser power system (100-200 kW peak) leads to expectations of αD_{max} in the 18-20 range. Such estimates are consistent with independent high power results (Ref. 16).

Wind and wind generated waves (throughout the entire wavelength spectrum from capillaries to off-shore swell) unquestionably influence system performance through a number of interactions, but few are overly significant except at the extremes--considered for our purposes to be 2-20 knots wind speed. Surface return energy from non-nadir scanner angles reaches the receiver only if capillary waves are excited sufficiently to present a large number of tiny facets perpendicular to the beam. These capillaries tend to die out below about 2 knots, and, as noted above, this leads to a reduced hit probability. On the other end of the spectrum, high winds generate waves with sufficient energy and depth to resuspend bottom sediments and decrease water clarity to unacceptable levels. From 2-20 knots, beam spreading through the air/sea interface due to wave slope augmented refraction is not large compared to beam spreading in the water column due to scattering. Surface return amplitudes at higher off-nadir scanner angles actually benefit slightly from higher winds where less variation of amplitude with angle is also noted.

If mean surface return signal strength versus altitude data are estimated with power law curves, the exponents thus obtained range between 1.0 and 2.0 for altitudes from 150-600m. No correlation between the value of the exponent and any variable or parameter (such as off-nadir angle or wind speed) could be established; rather, the value seems to be a complex function of these plus the direction of the beam relative to the wind direction. The median exponent value observed is approximately 1.3, which indicates that the surface returns generally contain a high specular component, rather than being diffuse in nature (for typical illuminated areas from 0.5-6m in diameter at the water's surface).

The effect of altitude on bottom return signal strength is indirect. The amount of bottom return energy reaching the receiver depends on the fraction of the bottom return energy refracted through the air/sea interface (in the direction of the receiver) within the field of view of the receiver. The factors determining that fraction are water clarity, depth, altitude, wind speed, and receiver field of view. An analytic model has been developed which calculates the field of view necessary to intercept 90% of the potential bottom return energy for specific values of the other parameters. This model is in good agreement with experimental data and can be used for future system design applications.

The off-nadir "scanner" angle affects both surface and bottom return signal strengths. Surface returns at nadir are quite strong and can easily exceed the input capabilities of the system. With increasing off-nadir angle, the returns decrease rapidly in the first five degrees and then much more slowly thereafter. Bottom return signal strength is also highest at nadir but falls off more gradually with increasing angles. A scanner pattern which does not intersect the nadir is highly desirable because it avoids the dynamic range problem caused by the strong nadir surface returns. Although the AOL was configured for a maximum off-nadir angle of 15°, extrapolations of test data indicate that angles of up to 30° or more may not be unreasonable. At such large angles, calculations of a depth bias due to pulse stretching from long slant ranges would become increasingly more important.

The transmitter beam divergence, varied from two to ten milliradians, had virtually no effect on results. The only potential restriction is that the beam must be large enough to provide high surface return probability; resolution is not degraded with a larger divergence because the beam spreading in the water is several orders of magnitude greater.

Dark, muddy bottoms, typical in Chesapeake Bay, caused no bottom detection difficulties. Reflectivities for sediments consisting of various grades of mud, sand, and shell fragments ranged between 4% and 12% with a median of approximately 9%. Significant bottom vegetation was present in neither test site. Future testing of the system will be planned for bottoms populated by various forms of broad and narrow leaf plants. It is expected that various types of vegetation will attenuate the bottom signal or cause a shallow bias in soundings.

Sunglint proved to be no problem in AOL testing, because scanner off-nadir angles were not large enough to permit viewing of the glint pattern at the 38° latitude of the test sites. For low latitudes, noon-time summer operations might be difficult, and a system with larger scan angle could experience a glint problem.

Vertical Accuracy:

Investigation of the basic sounding accuracy of the system to date has been based on data acquired in the "fixed" or non-scanning mode at various off-nadir angles. This technique permits simple comparisons with acoustic data and precludes additional errors due to possible uncertainties in wave correction procedures. (Scanning data contains large variations in air to sea slant range caused by scanner eccentricity and aircraft roll and pitch.) Wave correction procedures for scanning data based on careful modeling of the aircraft and scanner parameters are presently being investigated. Wave correction for non-scanning data is accomplished with a simple averaging technique based on altitude intervalometer data.

Accuracy is divided into two basic measures: precision and bias. Precision is a measure of self-consistency and is related to random noise, while bias errors are determined by comparison with an external "standard" and are fixed offset or "systematic" errors.

An upper bound on the actual system precision under given conditions can be estimated as the lower bound of the RMS deviation of given data about a linear fit to the data over a representative interval (typically chosen to be a single page of computer output: 40 points, or about 15 meters of track length). This is true, because this measure also unavoidably includes actual small bottom variations and residual uncorrected wave noise in addition to actual system random noise components. This worst case measure will henceforth be called "precision" for purposes of discussion.

A mean "precision" of 4-5 cm for data with reasonable signal strengths was observed during a low wind/wave test (without wave correction) with a 15° off-nadir scan angle. This value compares favorably with simulation results (Ref. 17) undertaken to derive a model of expected system performance based on laser pulse width and shape, charge digitizer gate width, photon arrival rates, pulse detection algorithms, and similar matters. At low bottom return signal strengths (several times the minimum detectable limit) the "precision" may typically increase into the 10-20 cm range (trending as predicted by the simulation). Because of limitations in the AOL altitude intervalometer (minimum discrete jumps of 15 cm, as operated), the mean precision for wave corrected data generally has a minimum of about 10 cm. Wave correction thus adds about 5 cm error to the optimum performance level, but on the other hand performs admirably for the more usual case where wave heights above 10 cm predominate.

Fully automated comparisons of AOL soundings with NOS acoustic soundings are not yet available (though pending), and the comparison has consequently involved comparisons of several data sets by hand--a tedious task. Results in general are encouraging. Datum free comparisons of laser and acoustic bottom profiles yield mean RMS deviations in the range of 5-15 cm. With appropriate datums applied, however, distinct biases of about 30 cm have been observed in several cases. Careful analysis of the data indicates no apparent fault with the basic techniques, and hardware anomalies are suspected. Ground test data (from simulated bottom and surface targets), presently being analyzed to test this hypothesis, appear to contain somewhat similar inconsistencies. Biases as a class are generally causal and hence correctable; the high "precision" noted in the data is considered to be a better measure of system performance at this point in time. Ultimately, biases of less than approximately ± 15 cm are desired. Detailed error budgets, calculated for the AOL and for an optimized design, indicate that this is a quite reasonable goal in the reasonably shallow coastal waters of interest.

5. Conclusions

1) The feasibility of obtaining high precision bathymetric soundings in a typical operational environment with a scanning airborne lidar system has been confirmed.

2) Excellent penetration ($\bar{\alpha}$ D $\cong$ 15) of typical coastal waters has been achieved with a relatively low power laser.

3) Performance in the scanning mode at off-nadir angles up to 15° is satisfactory for performing bathymetry.

4) The operational window for various system variables and environmental parameters is not unduly restrictive and should not lead to unreasonable mission constraints.

5) The mean precision of AOL soundings is excellent (typically less than 20 cm) and predictable with an existing model.

6) Biases of up to 30 cm presently noted in a limited number of soundings are slightly greater than NOS accuracy standards but are expected to be explainable (in terms of hardware instabilities) if not correctable. Such biases are not expected to appear in a well designed system.

7) Wave correction using altitude intervalometer data has been successfully demonstrated for non-scanning data. Further work is required to extend this result to scanning data.

8) Sophisticated peak detection and location software has been developed and is performing well in low signal-to-noise ratio conditions.

9) Separate studies indicate that a relatively high powered (200 kW peak), eye safe, lidar bathymetry system can be configured to operate from a small (Beech "King Air") aircraft (Ref. 18) and should provide a significant gain in cost-effectiveness over present acoustic techniques (Refs. 7 and 8).

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