NOAA Technical Report OTES 5

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Rockville, Md.
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U.S. DEPARTMENT OF COMMERCE
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AN ESTIMATE OF THE AREA SURVEYABLE WITH AN AIRBORNE LASER HYDROGRAPHY SYSTEM AT TEN U.S. SITES

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ABSTRACT. The amount of area surveyable with a proposed airborne laser hydrography system is estimated to total 82,000 km^2 for 10 U.S. sites.

1.0 INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) has been investigating airborne laser hydrography for several years. The technique uses an aircraft mounted, scanning beam, pulsed laser system to measure water depths. Bathymetric soundings resulting from a laser survey are intended for use by NOAA in the production of nautical charts. Separate studies (refs. 1, 2, 3) have shown that this technique can gather large quantities of accurate bathymetric soundings at a lower cost and with less manpower than present methods. The improved cost- and manpower-effectiveness for hydrographic surveying are the reasons for NOAA's interest.

Since laser hydrography is an optical technique, its ability to survey an area will be determined principally by the water clarity and water depth of the survey site. There must be a sufficient number of surveyable sites with large, contiguous areas of appropriate water clarity and depth in order to realize the desired cost and manpower savings. The purpose of this study was to estimate the laser surveyability of 10 sites on the U.S. East Coast, Great Lakes, and Gulf of Mexico for which water clarity and depth data already exist. Such an estimate is useful in assessing the applicability of laser hydrography to NOAA's surveying requirements.

2.0 BACKGROUND

Laser hydrography systems determine water depth by measuring the difference in arrival times at an airborne receiver of the sea surface reflection and the sea bottom reflection of a laser pulse (fig. 1). This time-of-flight difference is proportional to the water depth. Any depth can be measured if both the surface reflection and the bottom reflection can be detected in the received laser sounding waveform.

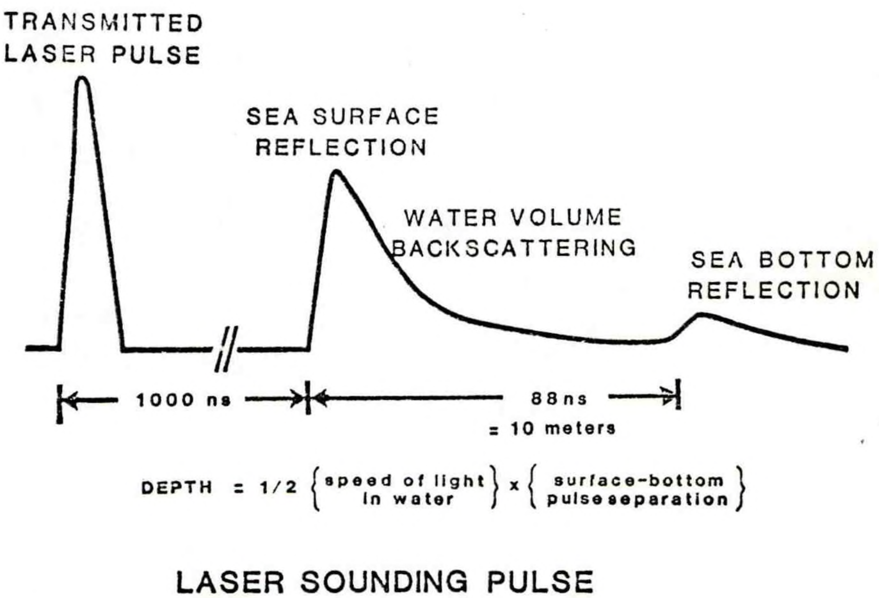

Figure 1. Received Laser Sounding Waveform

The strength of the surface reflection can be somewhat controlled through the selection of system operating parameters. The strength of the bottom reflection, however, will be determined largely by environmental parameters. For example, optical scattering and absorption in the water will attenuate the pulse. The reflectivity of the sea bottom will determine how much energy is reflected. Vegetation, breaking waves, and reflected sunlight will further complicate the detection of the bottom pulse.

As a laser sounding pulse propagates through the water, scattering and absorption will cause the pulse to be stretched and attenuated, thus lowering its peak power. Detailed simulations of laser pulse propagation in water (ref. 6) have produced two relationships which bound the peak power of the returning sea bottom reflection as detected by an airborne receiver. Where between the predictions of these two relationships the actual peak power of the returning pulse lies will be determined by the detailed optical properties of the water and the width of the transmitted laser pulse.

In areas of small diffuse optical depth (KD), eq. (1) is believed to describe the peak power of the returning pulse. Areas of small optical depth are those where scattering and absorption are small and/or the depth is shallow. In such areas the returning bottom pulse has approximately the same width as the transmitted pulse.

$$P_R = ARP_T \exp(-2KD) \qquad (1)$$

P_R = received power

A = a coefficient containing system and environmental parameters such as altitude, receiver aperture, optical transmission coefficients, etc.

R = sea bottom reflectivity

P_T = transmitted laser pulse peak power

K = optical diffuse attenuation coefficient of the water

D = water depth

In areas of large diffuse optical depth (KD), eq. (2) is believed to describe the peak power of the returning pulse. A significant amount of optical scattering takes place in such areas causing temporal and geometric dispersion or "pulse stretching" to occur. As a result, the returning pulse is longer than the transmitted pulse and of lower peak power than would be caused by absorption alone.

$$P_R = ARP_T \exp(-2k_pD - \ln D) \tag{2}$$

P_R, A, R, P_T, D as in eq. (1)

k_p = system attenuation coefficient for a system detecting power (typically $k_p > K$).

It can be seen from eqs. (1) and (2) that the maximum depth of successful sounding for any laser system is a function of the minimum detectable power of the airborne receiver $(P_R)_{min}$ and the other parameters of the equations. In addition, the maximum depth will depend on where between the bounds of eqs. (1) and (2) one is operating. This will be determined by the depth, the transmitted pulse width, and the single-scattering albedo (a parameter describing the fraction of the energy not absorbed at each optical scattering event). Again using results for the simulations of laser pulse propagation in water, it has been determined that eq. (3) is a reasonable, compromise relationship between eqs. (1) and (2). The empirically determined parameter $n = n(K)$ approximately equals $1.1K^{-1/9}$ for $0.05\ m^{-1} \leq K \leq 0.8\ m^{-1}$.

$$P_R = ARP_T \exp(-2nKD) \tag{3}$$

When the value of KD at a survey site is such that P_R equals the minimum power detectable by an airborne receiver, that system is operating at its maximum or "extinction" depth, and the value of KD is known as the "extinction coefficient" of the system. Once the extinction coefficient of a system is determined, the maximum depth penetrable by that system can be computed for any location using eq. (4) if the diffuse attenuation coefficient, K, of the water is known at the location.

$$D_{max} = \frac{(KD)_{max}}{K_{sounding\ site}} = \frac{\text{system extinction coefficient}}{\text{diffuse atten. coef. at sounding site}} \tag{4}$$

When the relationship

$$D_{sounding\ site} \leq D_{max} \tag{5}$$

holds, the laser will penetrate to the bottom and the site is considered surveyable. The surveyability of an entire area can be estimated using this technique if the system extinction coefficient has been established and if the diffuse attenuation coefficient and depth are known throughout the area.

3.0 METHODOLOGY

3.1 Establishing a System Extinction Coefficient

In 1977, the Airborne Oceanographic Lidar (AOL), an experimental airborne laser system belonging to NASA, was used by NOAA in a series of tests. More than 1.5 million laser depth soundings were gathered over a six-month period. One result of these tests was an empirical determination of the extinction coefficient for the AOL. That value was $(KD)_{max} = 2.5$.

The AOL, however, was not optimized for hydrography. Its receiver was extremely sensitive, but the low transmitted laser power (1 KW peak pulse power) and the restricted field of view (20 milliradians) reduced its extinction coefficient below that of a system designed specifically for hydrography. Eq. (3) and the AOL test results, however, can be used to predict the extinction coefficient of a system which transmits a more appropriate power level. Assuming that the two systems have the same minimum detectable power; that $(KD)_{max} = 2.5$ and $n = 1.0$ for the AOL tests; that on the average $n = 1.35$ for areas where the predicted system will be used ($K = 0.15\ m^{-1}$); and that the coefficient A is the same for both systems, eq. (3) yields:

$$[(KD)_{max}]_{predicted} = \frac{1}{2.7}\left[5 + \ln\left(\frac{P_T^{proposed}}{P_T^{AOL}}\right)\right]. \tag{6}$$

Values of predicted extinction coefficients for different values of transmitted power have been computed using eq. (6) and are shown in Table 1. Table 1 also presents values for system extinction coefficients expressed in terms of the beam attenuation coefficient, α, which, like K, is a parameter measuring water optical properties. The beam extinction coefficient, $(\alpha D)_{max}$, is a function of the single-scattering albedo, W_0. While K is believed to be a more representative parameter of the laser sounding pulse propagation than α, and the use of K has superceded the use of α, αwill be used in the balance of this report for two reasons. First, there are published relationships between α and other water optical parameters (see, for example, ref. 8). Second, the 1977 AOL experiments chose to use α for pragmatic reasons, and it came to be adopted as the convention. The shaded charts presented in section 4.0 are for $(\alpha D)_{max} = 20$.

Table 1. Effect of laser pulse peak power on system extinction coefficient

LASER PEAK PULSE POWER	PREDICTED EXTINCTION COEFFICIENT $(KD)_{MAX}$	PREDICTED BEAM EXTINCTION COEFFICIENT $(\alpha D)_{MAX}$ $(W_0=0.6)$ [1]	PREDICTED BEAM EXTINCTION COEFFICIENT $(\alpha D)_{MAX}$ $(W_0=0.8)$ [2]	PREDICTED BEAM EXTINCTION COEFFICIENT $(\alpha D)_{MAX}$ $(W_0=0.85)$ [3]
1 KW	2.5	5.4	10.0	12.5
100 KW	3.6	7.8	14.4	18.0
400 KW	4.1	8.9	16.4	20.5
800 KW	4.3	9.3	17.2	21.5

1. $W_0 = 0.6$ is the single-scattering albedo for clear, nearshore water off southern California.
2. $W_0 = 0.8$ is the upper bound for the single-scattering albedo for more turbid ocean-type coastal water.
3. $W_0 = 0.85$ is the single-scattering albedo for still more turbid estaurine type water.

The maximum laser pulse peak power that would be appropriate for the NOAA laser hydrography system is approximately 800 kilowatts.* At this power, the system would no longer be eye-safe for bystanders in the survey area according to ANSI Standard Z136.1 - 1976, American National Standard for the Safe Use of Lasers.

3.2 Determination of Laser Surveyable Areas Using Discrete Measurements of Water Clarity

With a system extinction coefficient established, eqs. (4) and (5) can be used to determine laser surveyability for areas of known water clarity and depth. Point measurements of water clarity parameters such as α have been made and archived by various investigators for a small number of U.S. locations (Appendix A). These data were used as follows. First, the data were converted to values of α using the relationships in Appendix B, and were then contoured by computer (ref. 4). The α contours were superimposed on NOAA nautical charts (the source of depth data) and values of α D inferred and contoured manually. General oceanographic knowledge was used to extend the estimates into regions of sparse water clarity data. Each α D contour represents the surveyability limit for a particular system extinction coefficient. The area enclosed by an α D contour, say $\alpha D = 20$, is expected to be surveyable by a laser system of that extinction coefficient. The areas enclosed by several values of α D were measured for each potential survey site. Sorting the water clarity data by season allowed investigation of the seasonal variations in surveyability.

*This assumes an operating altitude of 300 m and a beam divergence of 2.2 milliradians (full angle).

These existing data were convenient but could introduce errors in the estimates of laser surveyable area in several ways. First, the identity of the investigators, the protocol followed, and the environmental conditions affecting the measurements were not known. These factors could affect the accuracy and comparability of the measurements. Second, the archived data were not uniformly distributed in space and time. Frequently they were collected for a specific purpose, such as an environmental impact statement, and thus were not well located for a general characterization of a body of water. Finally, the actual data themselves could be significantly in error. This occurs because the measurements are difficult to make accurately, and because several different measures of water clarity were gathered and subsequently converted to values of α using relationships which are only approximately true. The lack of dense, uniformly distributed, high quality data is the largest source of error in this report. It is felt that individual measurements of water clarity may be in error by as much as ± 25%. Unfortunately, no better data are known to exist.

NOS nautical charts were used to provide the depth information required by eq. (4). These charts can introduce two sources of error in the laser surveyability estimates. First, all depths are given for mean low water or, in the case of the Great Lakes, referenced to the 1955 low water datum. If a laser survey is performed at a different state of the tide or at a different water level, the water will almost always be deeper in which case less of the area can be surveyed. The tide or water level range is included in the report results along with an estimate of the magnitude of this effect. A second characteristic of nautical charts that could introduce errors is that shallow depths are preferentially shown on the charts for reasons of navigation safety. This preferential selection will make the area appear shallower than it is and cause an optimistic estimate of the area surveyable by laser. The magnitude of this error could not be quantified.

Bottom reflectivity may also affect the amount of area surveyable by laser [see eq. (2)]. When the AOL extinction coefficient was determined experimentally in 1977, it was determined for the bottom reflectivities existing at the experiment site. The extrapolations to the other system extinction coefficients in Table 1 assume the same bottom reflectivities. Fortunately, laser system penetration is only weakly dependent on bottom reflectivity (linear instead of exponential as with depth and water clarity). Errors in laser surveyability due to varying bottom reflectivities are thus believed to be small.

A final source of error was the manual contouring of the α D product. This technique required examining NOS nautical charts for depth data and overlaying them with α data and α contours. Values of depth and water clarity were manually interpolated to get estimates at common points. Contours of the α D product were then manually drawn. Using this method, the computed surveyability could vary as much as 25% for estimates made of one area by several different people.

3.3 Determination of Laser Surveyable Areas Using Aerial Photography

Aerial photographs were also used to estimate the amount of area surveyable by laser. NOAA routinely performs aerial photography to determine the location of the shoreline and to gather photogrammetric information of the near-shore area. A series of such photographs was examined by experienced NOS photogrammetrists in 1976, and the areas where the sea bottom was visible were delineated on NOS nautical charts. The extinction coefficient of this photobathymetric measurement has been estimated to be approximately $\alpha D \leq 2$ (ref. 5). The laser surveyable area can be inferred from the photobathymetric measurements for any laser system extinction coefficient by assuming the water clarity to be constant at increasing distances from shore and noting that an $\alpha D = 20$ system will penetrate 10 times deeper than an $\alpha D = 2$ system for a given water clarity. A surveyability contour for $\alpha D = 20$ (or 15, or 10) can thus be drawn using the $\alpha D = 2$ photobathymetric data. Such contours were drawn and the area enclosed by them was measured.

An advantage of photographic source data over the discrete measurements is that photos give 100% coverage of the area. The photomeasurements, however, show water optical properties for only one instant. No seasonal dependence was determinable, nor was there any averaging of data over several months or years. It is thus not known if the surveyability estimates made from aerial photos are typical or atypical.

The estimate of $\alpha D = 2$ was one approximation which will strongly affect the accuracy of laser surveyability estimates. Two additional assumptions were used. First, it was assumed that water clarity remained constant or improved as depth increased beyond the ability of the photographs to penetrate. This is consistent with the decreased resuspension of sediment by surface waves as the water gets deeper. Second, it was assumed that the bottom reflectivity was constant or increased as depth increased. Neither of these two assumptions is seen as a dominant source of error in estimating laser surveyability from photographs.

Errors introduced by tides and chart characteristics as described in Section 3.2 also apply to surveyability estimates made from aerial photographs. Errors introduced by α D contouring do not apply to this technique.

4.0 RESULTS

The results of the laser surveyability estimates are presented by geographic location. Graphs have been drawn to show the amount of area surveyable at each location for different values of system beam extinction coefficients up to $(\alpha D)_{max} = 20$. For those areas estimated from discrete measurements of water clarity, a different curve is drawn for each season. The surveyable area is also plotted as a percentage of the total area for enclosed sites such as Tampa Bay.

Three other items are included for each site. First, the pertinent information related to the site and the surveyability estimate has been collated into a table. Second, the cumulative distribution of depths was plotted. These graphs were used to estimate the effect of tides or water levels on the surveyability estimates. Finally, a photograph of the nautical chart is shown with the laser surveyable area shaded for $\alpha D = 20$. The "percent surveyable" estimates on the photographs are slightly different from those on the graphs. This was caused by rounding and by slightly different area boundaries having been used for the graphs and photographs.

Table 2 summarizes the results for all the areas and gives a subjective statement of confidence in each estimate. Tables 3 through 12 and Figs. 2 through 31 starting on page 22 show the actual results.

Table 2. Estimates of the maximum amount of area surveyable by laser at 10 U.S. sites ($\alpha D = 20$).

LOCATION	ESTIMATED MAX. AREA SURVEYABLE	ESTIMATED MAX DEPTH REACHED	OPTIMUM SEASON	CONFIDENCE IN ESTIMATES
CHESAPEAKE BAY (NORTHERN HALF)	1,460 KM^2	9-10 METERS	AUTUMN	LOW
CHESAPEAKE BAY (SOUTHERN HALF)	2,850 KM^2	9-11 METERS	AUTUMN	MEDIUM
JAMES RIVER (LOWER END)	161 KM^2	3-4 METERS	SUMMER	LOW
TAMPA BAY	785 KM^2	10-11 METERS	-----	MEDIUM
NANTUCKET SOUND	2,970 KM^2	18 METERS	-----	MEDIUM
GULF OF MEXICO (ONE SECTION NORTH OF TAMPA BAY)	6,500 KM^2	21-30 METERS	-----	LOW
LAKE ERIE	24,160 KM^2	18 METERS	SUMMER	LOW
LAKE ONTARIO	7,125 KM^2	8-11 METERS	WINTER	LOW
LAKE HURON	35,670 KM^2	35 METERS	SUMMER	LOW
NEW YORK HARBOR	280 KM^2	7 METERS	SUMMER	LOW

5.0 CONCLUSIONS

The results of this study indicate that there is a large amount of area surveyable by laser. A maximum total of 82,000 km^2 was estimated to be within reach of the planned NOAA airborne laser hydrography system at the 10 U.S. sites studied. 82,000 km^2 is $1\frac{1}{2}$ times the design lifetime capability of that system*.

The area surveyable was found to be strongly dependent on the capability of the laser system. For low system extinction coefficients, only the shallow, near-shore area was found to be surveyable. As the system extinction coefficient was increased, the surveyable area increased and encompassed deeper water. It was not clear at the beginning of the study that this phenomenon would occur because laser surveyability is as dependent on water clarity as on depth. If the water clarity improved as fast or faster than the depth increased, then surveyable deep water could conceivably have been found adjacent to unsurveyable shallow water. This was generally not found to be the case. Water depth tended to vary faster and over a broader range of values than water clarity and was thus found to be the more important parameter limiting laser surveyability.

A certain amount of structure was seen in the surveyable areas contoured from discrete measurements of water clarity. Patches of surveyable area were found in unsurveyable areas and vice-versa. Also, the edges of the surveyable

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*assuming an 8-year design lifetime and 6,900 km^2 surveyed per year (refs. 1, 3) areas exhibited a "fingered" appearance. The size of these structures, as they appear on the charts, seemed to be the same regardless of the scale of the chart. It is thus felt that they are artifacts of the technique rather than the actual patchiness expected to be occurring naturally. As a result, this study is unable to make any conclusions about small scale gaps in surveyablity.

A significant seasonal dependency was observed. It is estimated that surveying at the optimum season could increase the amount of surveyable area by 10% to 50% (for α D = 20) over the worst season. No single season, however, was found to be optimum for all locations.

The estimates of laser surveyable area developed in this report should be interpreted cautiously. There are many uncontrollable sources of error both in the data and in the methodology as described in Sections 3.2 and 3.3. Also, the results are not entirely self-consistent. One subarea of southern Chesapeake Bay, for example, was determined to be surveyable by a system of extinction coefficient α D = 12, but not surveyable by a more capable system with α D = 16. This inconsistency represents "noise" in the manual portion of the data analysis methodology.

Another reason to interpret these study results cautiously is that the latest knowledge concerning the penetration of laser sounding pulses through water was not available when data were analyzed. Consequently, results tend to be overoptimistic in very deep water. Incidents of 120 meter penetration in Lake Huron, estimated using the methodology of this study, conflict with theoretical estimates which consider the dependence of the beam extinction coefficient (α D)$_{max}$ on the single scattering albedo, W_0. This dependency tends to reduce (α D)$_{max}$ in very clear water (small W_0), as seen in table 1.

The study was able, however, to find some anticipated phenomena. The mouths of rivers were expected to be less surveyable than the bodies of water into which they emptied. This was observed in most cases with the James, York, and Rappahannock Rivers providing three examples in southern Chesapeake Bay. Also, unsurveyable areas were found as anticipated around the industrial cities along Lake Erie. The ability to find such major phenomena allows one to conclude that the results of this study are not entirely specious.

Several questions pertaining to laser surveyability were not addressed by this study. The small scale horizontal structure of the surveyable area, and the vertical structure and short term temporal variability in the water optical properties all need further investigation.

In conclusion, it is felt that the results of this study are encouraging. This particular methodology with these particular data indicates that a large amount of laser surveyable area exists. It is also concluded, however, that the estimate is extremely difficult to make and subject to large errors. Other methods of estimating laser surveyable area should also be tried in order to build a preponderance of evidence concerning the suitability of airborne laser hydrography for NOAA.

ACKNOWLEDGEMENTS

This particular study was spread over a long period of time and involved a large number of people, particularly in the labor intensive manual contouring of αD and in the planimetering. The authors wish to express their appreciation to: Gary Farr, Earl Frederick, Tim Rulon, Larry Gray, Debora Williams, Carol Hurley, and Christy Bumanis for their help.

REFERENCES

1. Enabnit, D. B., Goodman, L. R., Young, G. K., Shaughnessy, W. J., "The Cost Effectiveness of Airborne Laser Hydrography," NOAA Technical Memorandum NOS 26, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C., December 1978.

2. "Airborne Laser Hydrography - A Briefing Prepared for the Director of the National Ocean Survey," prepared by the Office of Marine Technology, NOS, May 11, 1979.

3. Enabnit, D. B., "Airborne Laser Hydrography - FY 1982 Issue Paper," Engineering Development Laboratory, Office of Marine Technology, NOS, Version 2, May 1, 1980.

4. "Contour Plot System (CPS-1), User's Manual," Unitec, Inc., Vol. I, 1973.

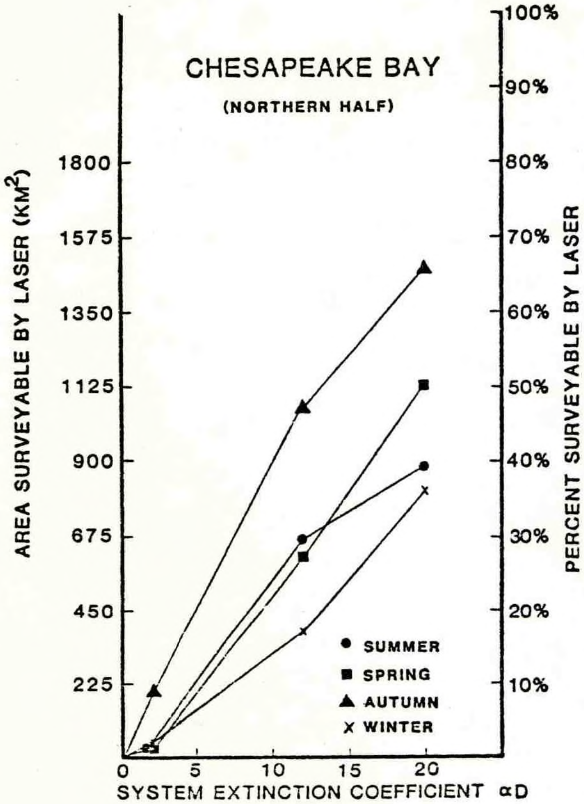
5. Keller, M., Photogrammetric Research Branch, Photogrammetry Division, NOS, (private communication).

6. Guenther, G. C., and Thomas, R. W. L., "Monte Carlo Simulations of the Effects of Underwater Propagation on the Penetration and Depth Measurement Bias of an Airborne Laser Bathymeter," NOAA Technical Memorandum OTES 01, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C., March 1981.

7. Witt, A. K., Shannon, J. G., Rankin, M. B., and Fuchs, L. A., "Air/Underwater Laser Radar Test Results, Analysis, and Performance Predictions," Naval Air Development Center Report No. NADC-76005-20, (1976). (Report is classified "CONFIDENTIAL").

8. Gordon, H. R., and Wouters, A. W., "Some Relationships Between Secchi Depth and Inherent Optical Properties of Natural Waters," Applied Optics, 17, 21, 3341.

TABLES AND FIGURES



LOCATION	- NORTHERN CHESAPEAKE BAY (38°10' LAT TO 39°22' LAT)
CHART USED FOR DEPTHS	- 12260
CHART SCALE	- 1:197,250
TOTAL AREA	- 2,200 KM^2
TYPE OF DATA	- DISCRETE MEASUREMENTS
NUMBER OF DATA STATIONS	- SPRING - 81 SUMMER - 76 AUTUMN - 72 WINTER - 45
AVERAGE DATA STATION DENSITY	- SPRING - 1 PER 28 KM^2 SUMMER - 1 PER 30 KM^2 AUTUMN - 1 PER 30 KM^2 WINTER - 1 PER 50 KM^2
TIME SPAN OF DATA	- SPRING - 1960-74 SUMMER - 1960-74 AUTUMN - 1960-74 WINTER - 1960-74
OPTICAL PARAMETERS MEASURED	- SECCHI DEPTHS, SOME SUSPENDED SOLIDS
MEAN RANGE OF TIDES	- 0.67 METER
EFFECT ON SURVEYABILITY OF TIDES/WATER LEVEL	- -3%
TYPICAL MAX DEPTH SURVEYABLE	- 9-10 METERS
CONFIDENCE IN ESTIMATES	- LOW

Figure 2. (upper left) Chesapeake Bay (northern half) - estimated laser surveyable area at mean low water

Table 3. (upper right) Chesapeake Bay (northern half) - supporting data for laser surveyability estimate

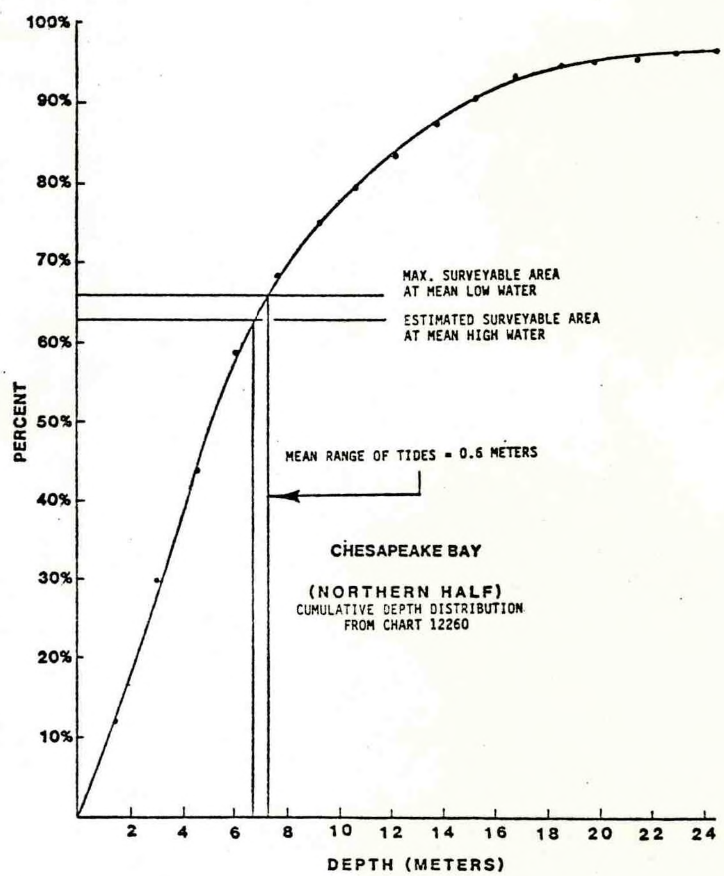


Figure 3. (lower right) Chesapeake Bay (northern half) - effect of tides on surveyability estimate

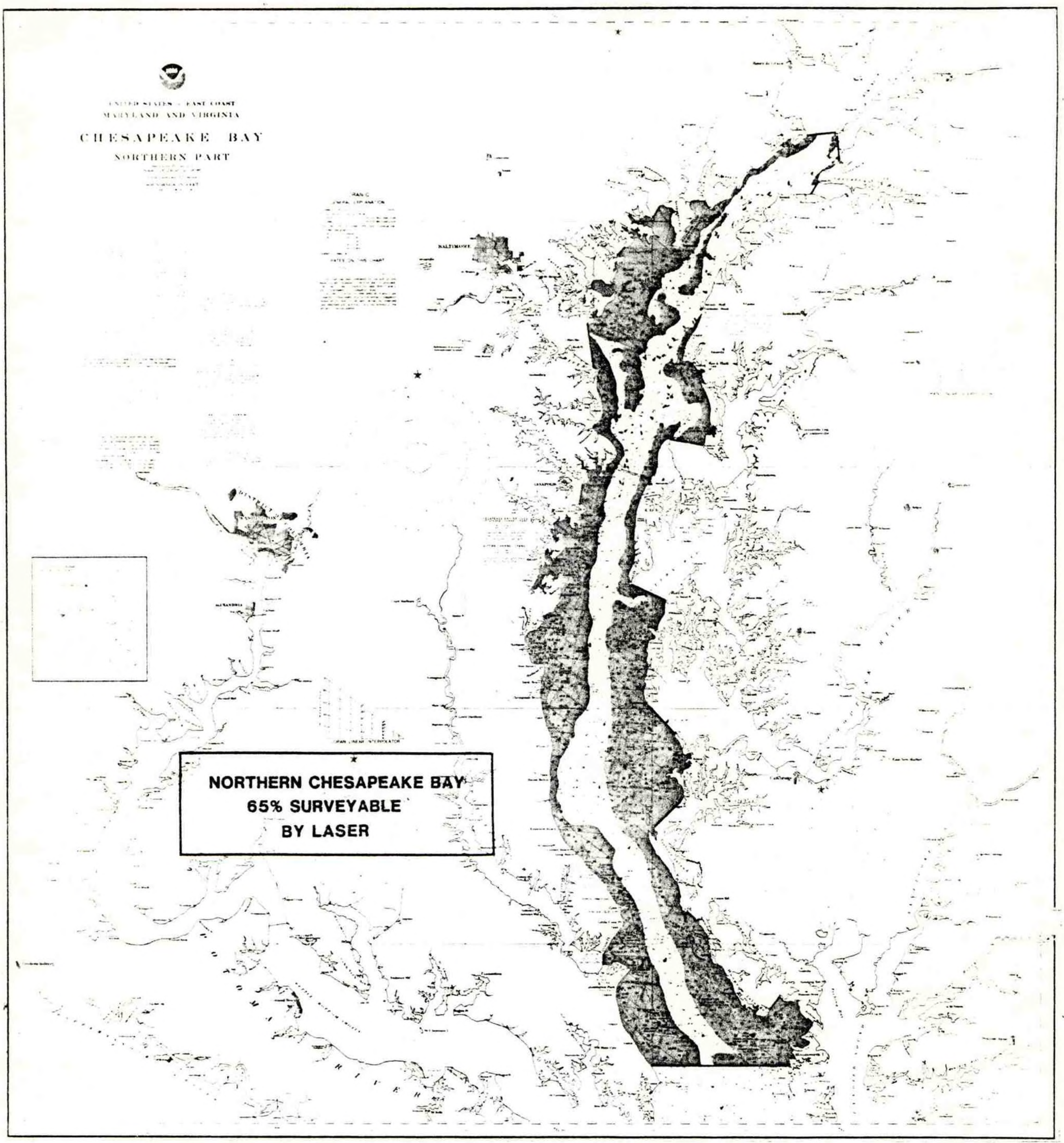
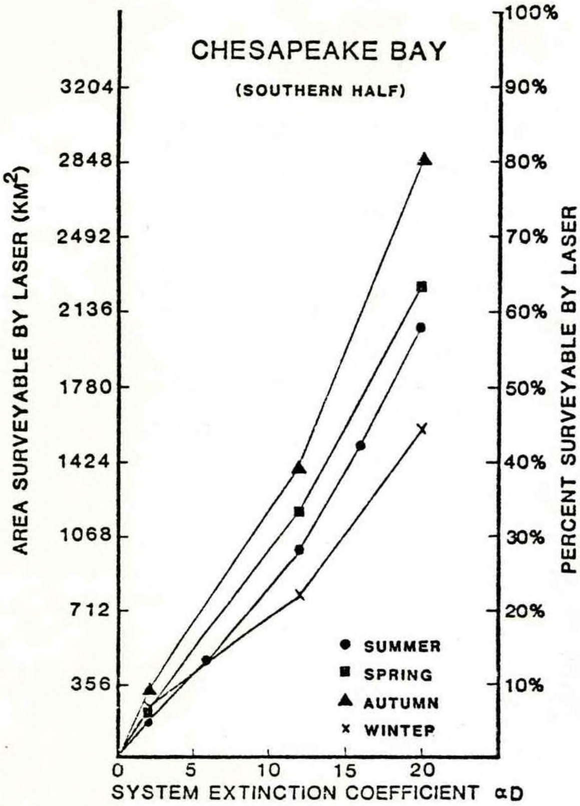


Figure 4. Chesapeake Bay (northern half) - chart of estimated laser surveyable area for $\alpha D = 20$.



LOCATION	- SOUTHERN CHESAPEAKE BAY (76° LONG TO 37°58' LAT)
CHART USED FOR DEPTHS	- 12220
CHART SCALE	- 1:200,000
TOTAL AREA	- 3,560 KM^2
TYPE OF DATA	- DISCRETE MEASUREMENTS
NUMBER OF DATA STATIONS	- SPRING - 83 SUMMER - 154 AUTUMN - 178 WINTER - 58
AVERAGE DATA STATION DENSITY	- SPRING - 1 PER 43 KM^2 SUMMER - 1 PER 23 KM^2 AUTUMN - 1 PER 20 KM^2 WINTER - 1 PER 61 KM^2
TIME SPAN OF DATA	- SPRING - 1960-74 SUMMER - 1960-74 AUTUMN - 1960-74 WINTER - 1960-74
OPTICAL PARAMETERS MEASURED	- SECCHI DEPTHS, SOME SUSPENDED SOLIDS
MEAN RANGE OF TIDES	- 0.67 METER
EFFECT ON SURVEYABILITY OF TIDES/WATER LEVEL	- -4%
TYPICAL MAX DEPTH SURVEYABLE	- 9-10 METERS
CONFIDENCE IN ESTIMATES	- MEDIUM

Figure 5. (upper left) Chesapeake Bay (southern half) - estimated laser surveyable area at mean low water

Table 4. (upper right) Chesapeake Bay (southern half) - supporting data for laser surveyability estimate

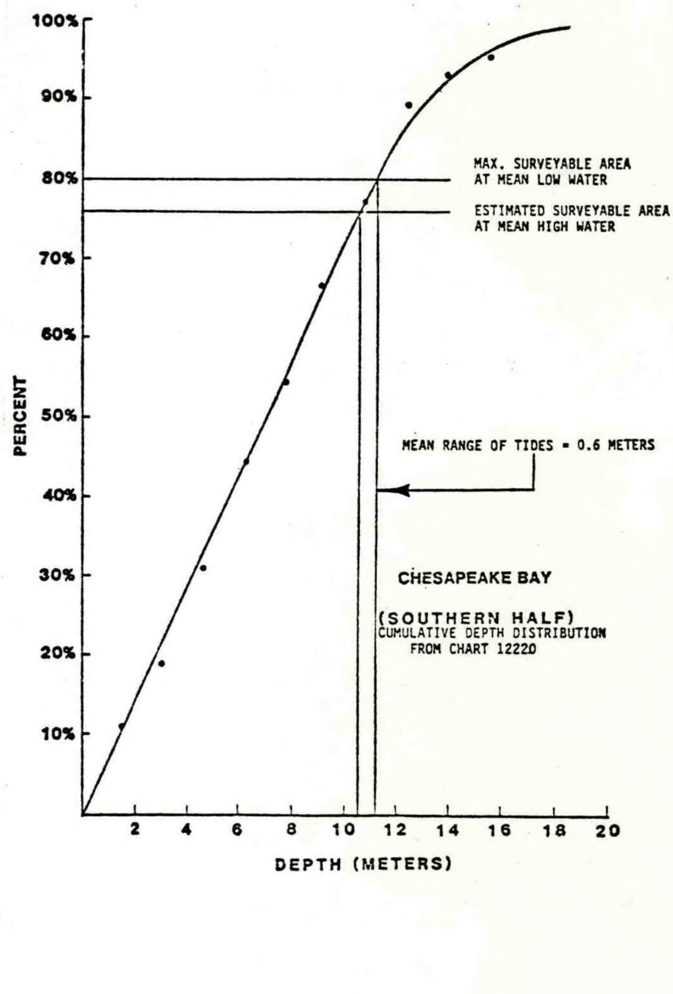


Figure 6. (lower right) Chesapeake Bay (southern half) - effect of tides on surveyability estimate

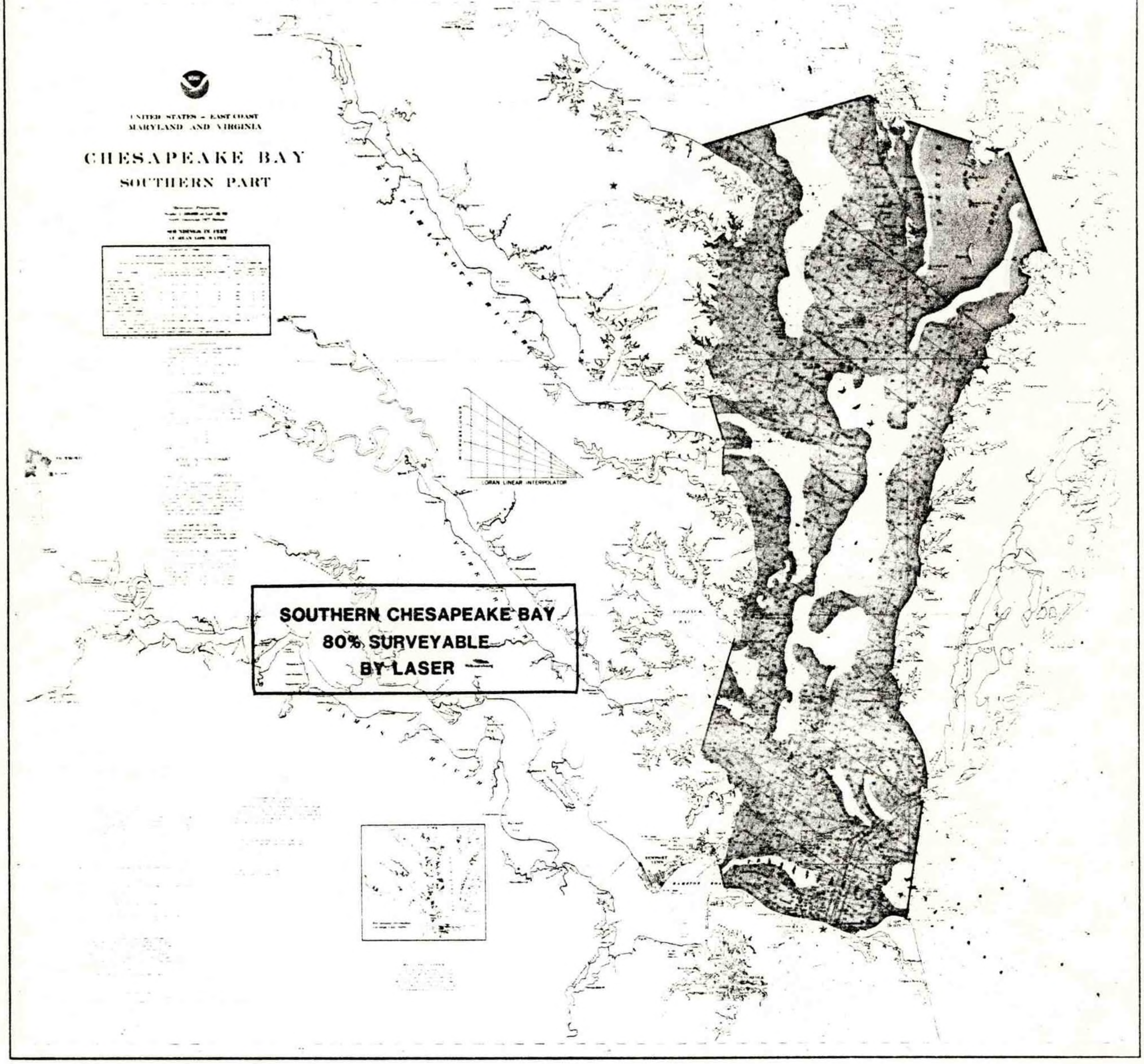
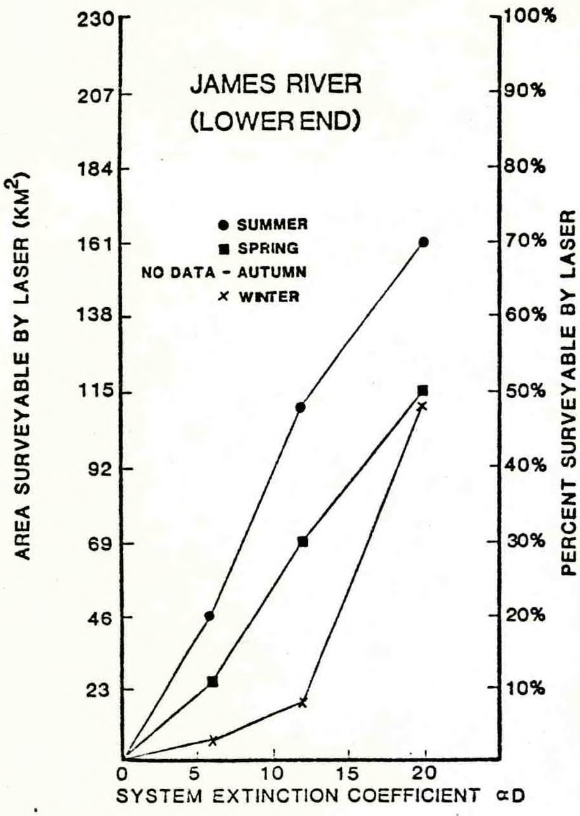


Figure 7. Chesapeake Bay (southern half) - chart of estimated laser surveyable area for $\alpha D = 20$.

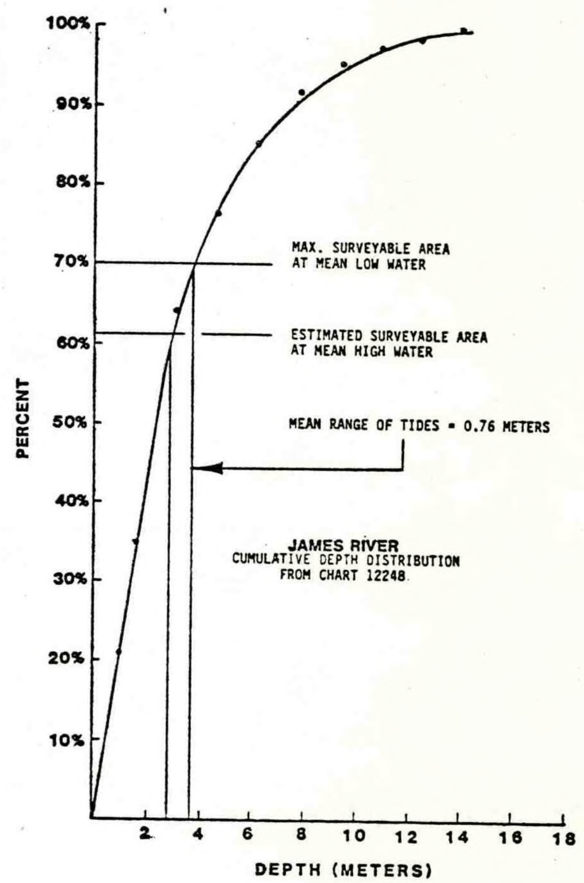


LOCATION	- JAMES RIVER (LOWER END - 36°55' LAT TO 37°10' LAT)
CHART USED FOR DEPTHS	- 12248
CHART SCALE	- 1:40,000
TOTAL AREA	- 230 KM^2
TYPE OF DATA	- DISCRETE MEASUREMENTS
NUMBER OF DATA STATIONS	- SPRING - 105 SUMMER - 123 AUTUMN - 44 WINTER - 34
AVERAGE DATA STATION DENSITY	- SPRING - 1 PER 2 KM^2 SUMMER - 1 PER 2 KM^2 AUTUMN - 1 PER 5 KM^2 WINTER - 1 PER 7 KM^2
TIME SPAN OF DATA	- SPRING - 1960-74 SUMMER - 1960-74 AUTUMN - 1960-74 WINTER - 1960-74
OPTICAL PARAMETERS MEASURED	- SECCHI DEPTHS, SOME SUSPENDED SOLIDS
MEAN RANGE OF TIDES	- 0.75 METER
EFFECT ON SURVEYABILITY OF TIDES/WATER LEVEL	- -8%
TYPICAL MAX DEPTH SURVEYABLE	- 3-4 METERS
CONFIDENCE IN ESTIMATES	- LOW

Figure 8. (upper left) James River (lower end) - estimated laser surveyable area at mean low water

Table 5. (upper right) James River (lower end) - supporting data for laser surveyability estimate

Figure 9. (lower right) James River (lower end) - effect of tides on surveyability estimate



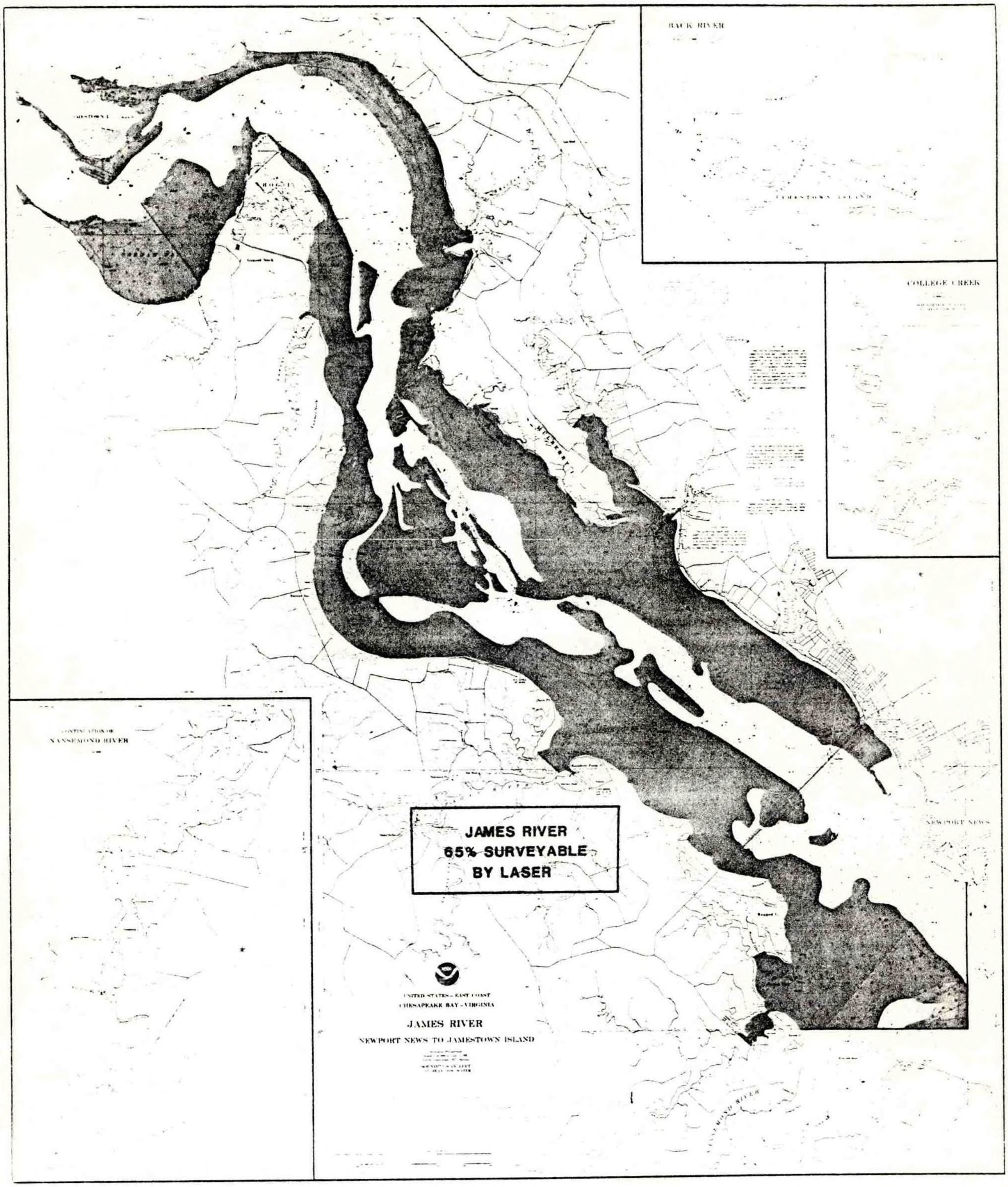
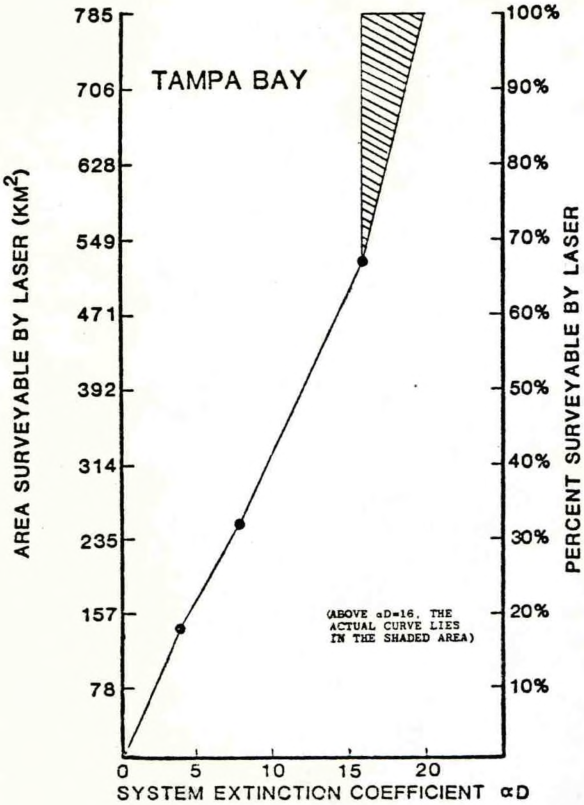


Figure 10. James River (lower end) - chart of estimated laser surveyable area for $\alpha D = 20$.



LOCATION	- TAMPA BAY
CHART USED FOR DEPTHS	- 11412, 11413, AND 11414
CHART SCALE	- 1:40,000
TOTAL AREA	- 785 KM^2
TYPE OF DATA	- AERIAL PHOTOGRAPHS
NUMBER OF DATA STATIONS	- SPRING - N/A SUMMER - " AUTUMN - " WINTER - "
AVERAGE DATA STATION DENSITY	- SPRING - N/A SUMMER - " AUTUMN - " WINTER - "
TIME SPAN OF DATA	- SPRING - ONE INSTANT SUMMER - " AUTUMN - " WINTER - "
OPTICAL PARAMETERS MEASURED	- PHOTO PENETRATION
MEAN RANGE OF TIDES	- 0.67 METER
EFFECT ON SURVEYABILITY OF TIDES/WATER LEVEL	- -1%
TYPICAL MAX DEPTH SURVEYABLE	- 10-11 METERS
CONFIDENCE IN ESTIMATES	- MEDIUM

Figure 11. (upper left) Tampa Bay - estimated laser surveyable area at mean low water

Table 6. (upper right) Tampa Bay - supporting data for laser surveyability estimate

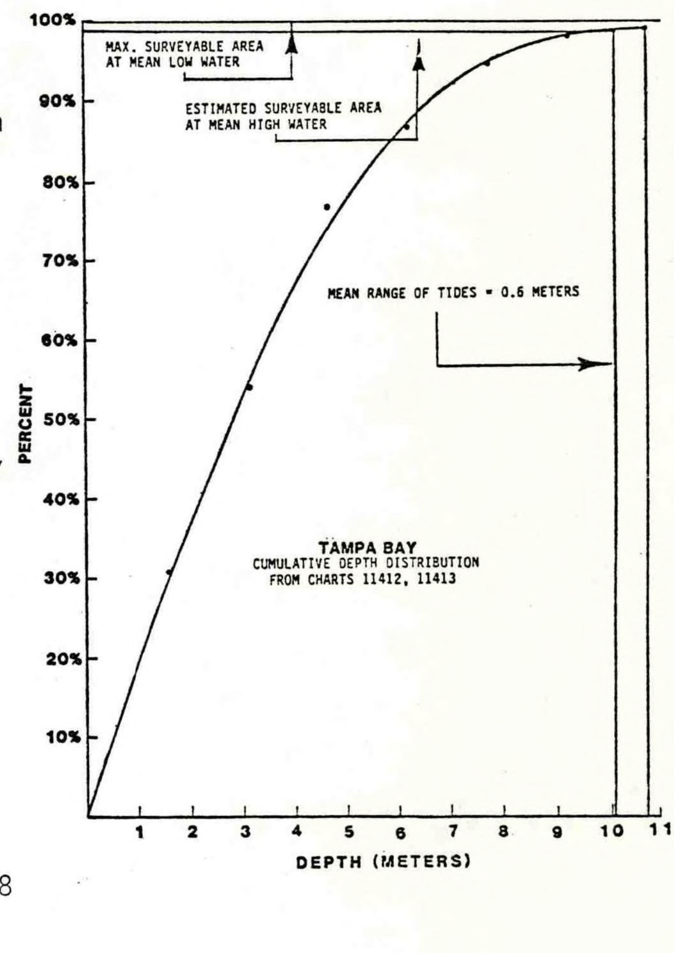


Figure 12. (lower right) Tampa Bay - effect of tides on surveyability estimate

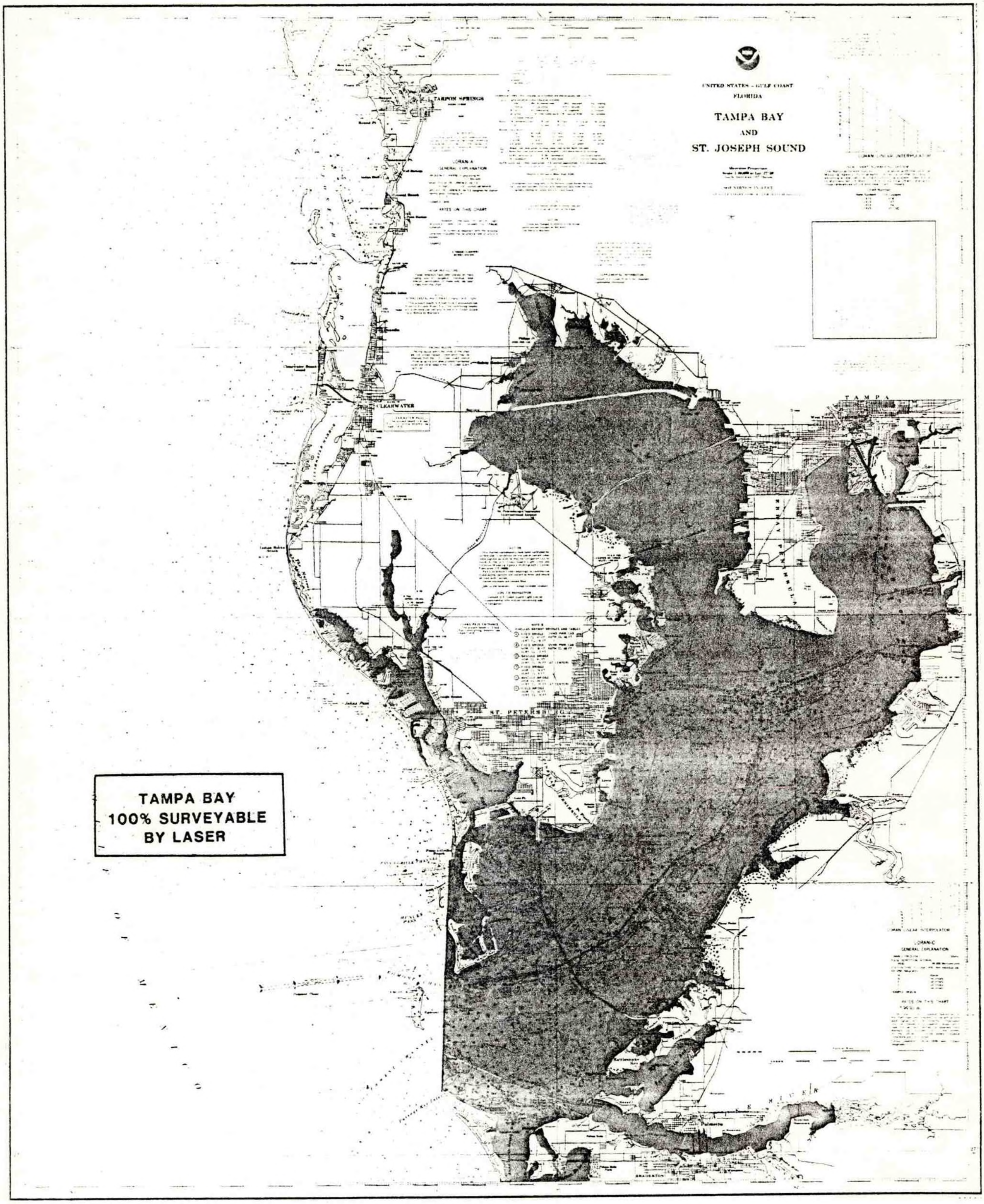
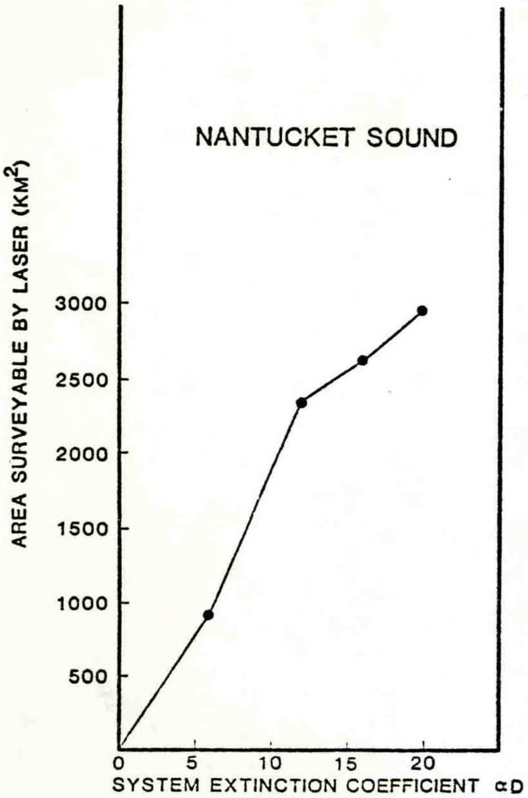


Figure 13. Tampa Bay - chart of estimated laser surveyable area for $\alpha D = 20$.



LOCATION	- NANTUCKET SOUND
CHART USED FOR DEPTHS	- 13237
CHART SCALE	- 1:80,000
TOTAL AREA	- 3,000 KM^2
TYPE OF DATA	- AERIAL PHOTOGRAPHY
NUMBER OF DATA STATIONS	- SPRING - N/A SUMMER - " AUTUMN - " WINTER - "
AVERAGE DATA STATION DENSITY	- SPRING - N/A SUMMER - " AUTUMN - " WINTER - "
TIME SPAN OF DATA	- SPRING - ONE INSTANT SUMMER - " AUTUMN - " WINTER - "
OPTICAL PARAMETERS MEASURED	- PHOTO PENETRATION
MEAN RANGE OF TIDES	- 1.0 METER
EFFECT ON SURVEYABILITY OF TIDES/WATER LEVEL	- -2%
TYPICAL MAX DEPTH SURVEYABLE	- 18 METERS
CONFIDENCE IN ESTIMATES	- MEDIUM

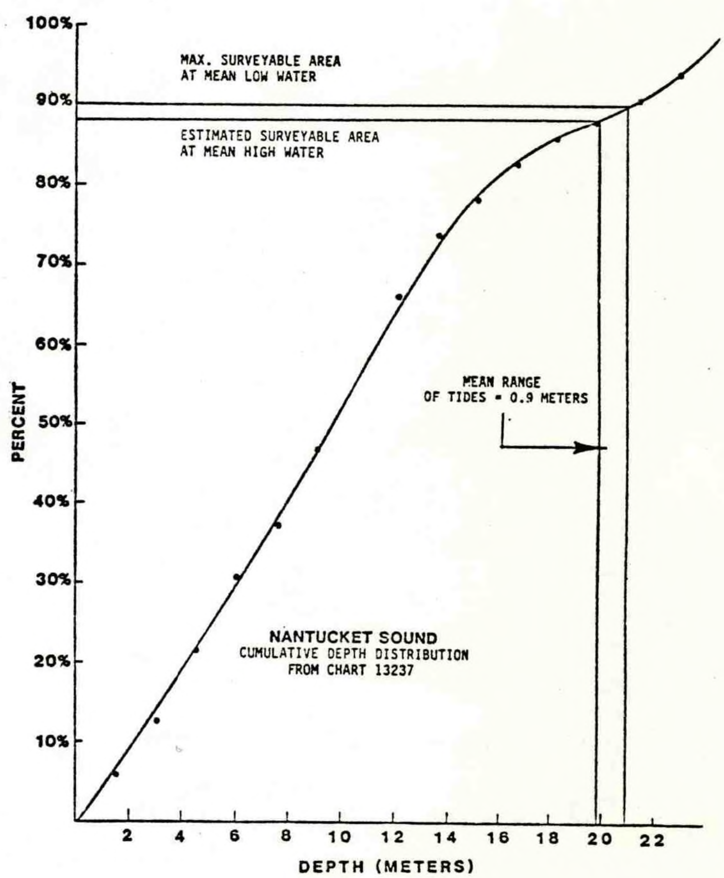


Figure 14. (upper left) Nantucket Sound - estimated laser surveyable area at mean low water

Table 7. (upper right) Nantucket Sound - supporting data for laser surveyability estimate

Figure 15. (lower right) Nantucket Sound - effect of tides on surveyability estimate

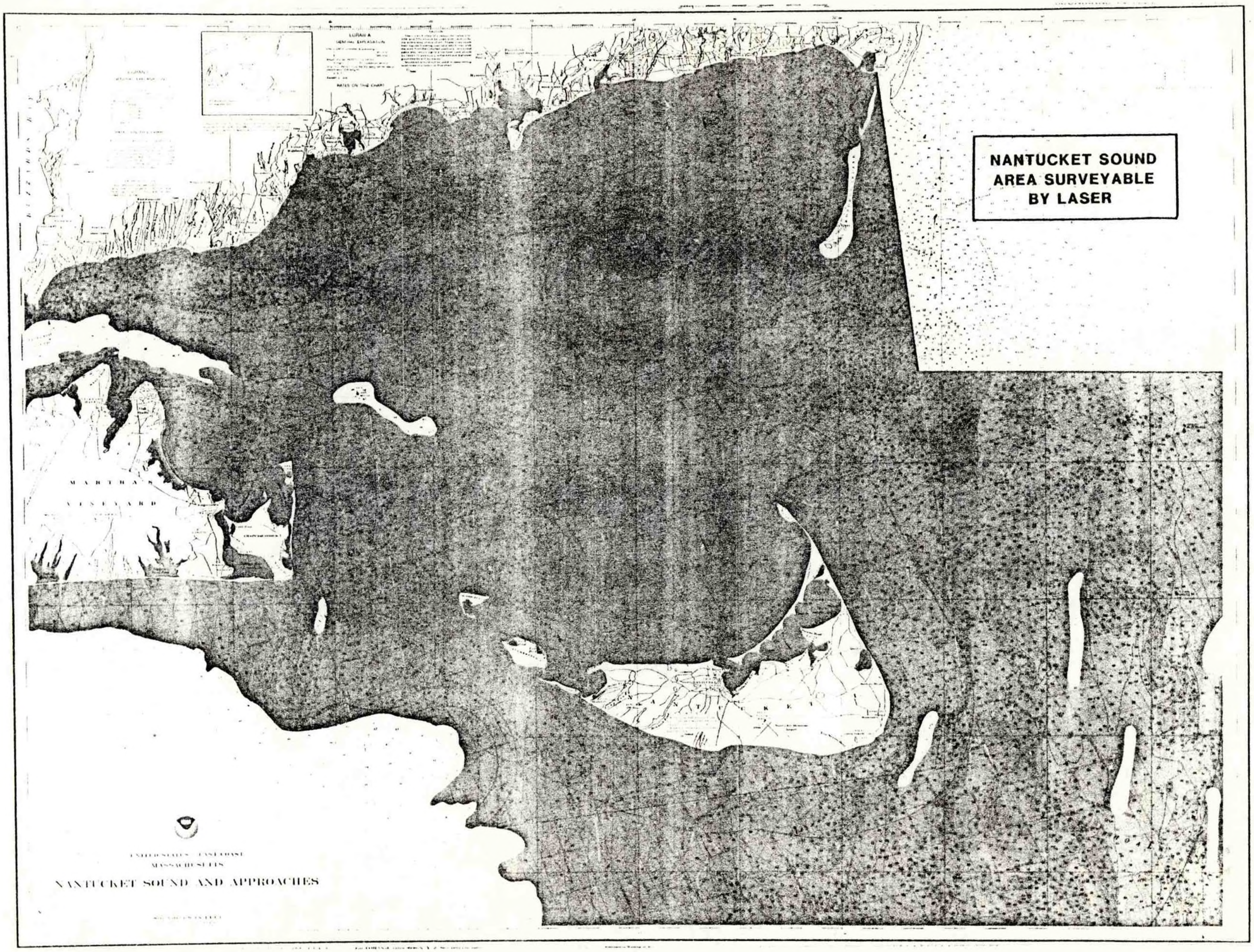
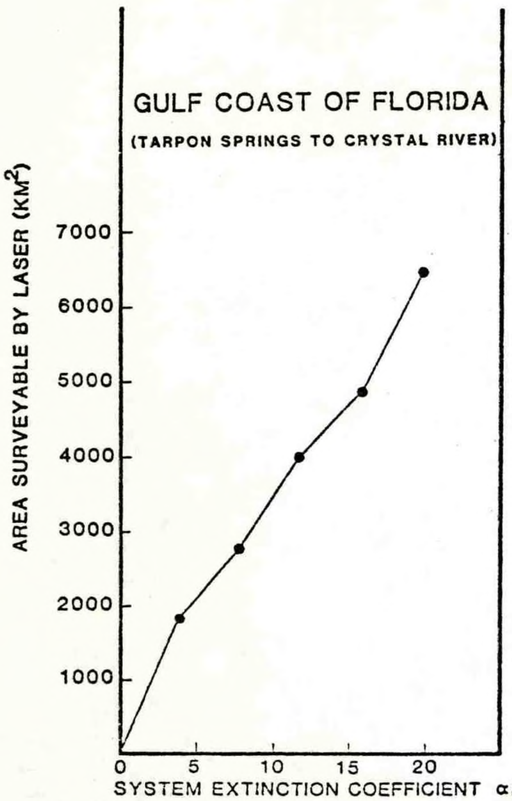


Figure 16. Nantucket Sound - chart of estimated laser surveyable area for $\alpha D = 20$.



LOCATION	- GULF OF MEXICO (FLORIDA COAST 28°10' LAT TO 28°55' LAT)
CHART USED FOR DEPTHS	- 11400
CHART SCALE	- 1:456,394
TOTAL AREA	- 6,500 KM^2
TYPE OF DATA	- AERIAL PHOTOGRAPHS
NUMBER OF DATA STATIONS	- SPRING - N/A SUMMER - " AUTUMN - " WINTER - "
AVERAGE DATA STATION DENSITY	- SPRING - N/A SUMMER - " AUTUMN - " WINTER - "
TIME SPAN OF DATA	- SPRING - ONE INSTANT SUMMER - " AUTUMN - " WINTER - "
OPTICAL PARAMETERS MEASURED	- PHOTO PENETRATION
MEAN RANGE OF TIDES	- 0.67 METER
EFFECT ON SURVEYABILITY OF TIDES/WATER LEVEL	- -4% (-260 KM^2)
TYPICAL MAX DEPTH SURVEYABLE	- 21-30 METERS
CONFIDENCE IN ESTIMATES	- LOW

Figure 17. (upper left) Gulf of Mexico (one section north of Tampa Bay) - estimated laser surveyable area at mean low water

Table 8. (upper right) Gulf of Mexico (one section north of Tampa Bay) - supporting data for laser surveyability estimate

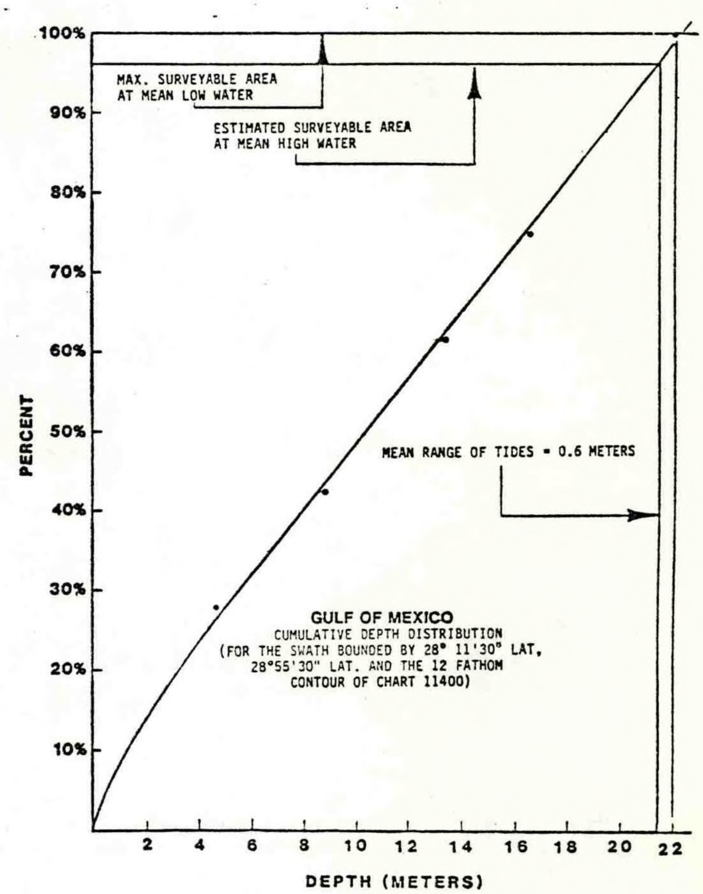


Figure 18. (lower right) Gulf of Mexico (one section north of Tampa Bay) - effect of tides on surveyable area

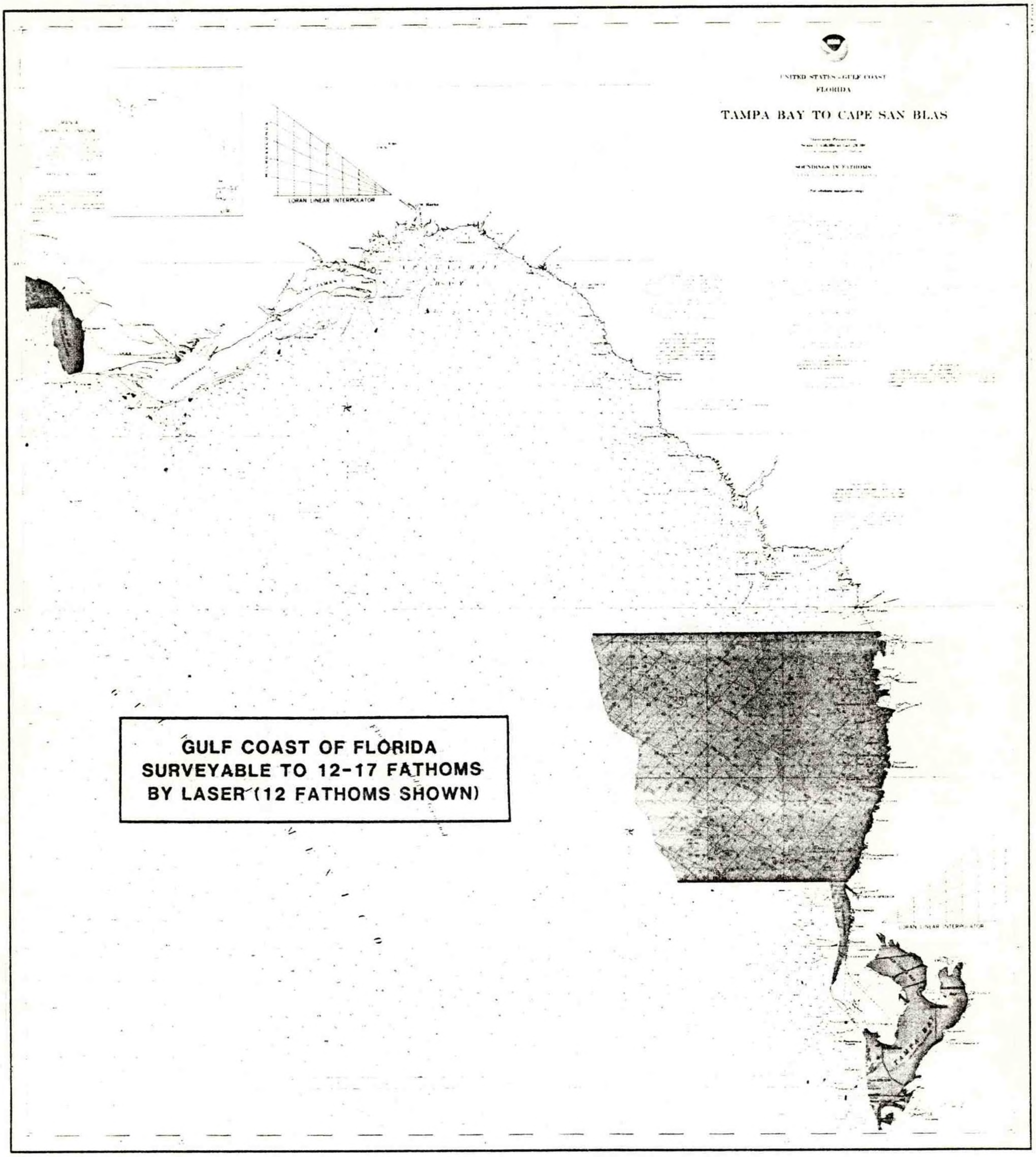
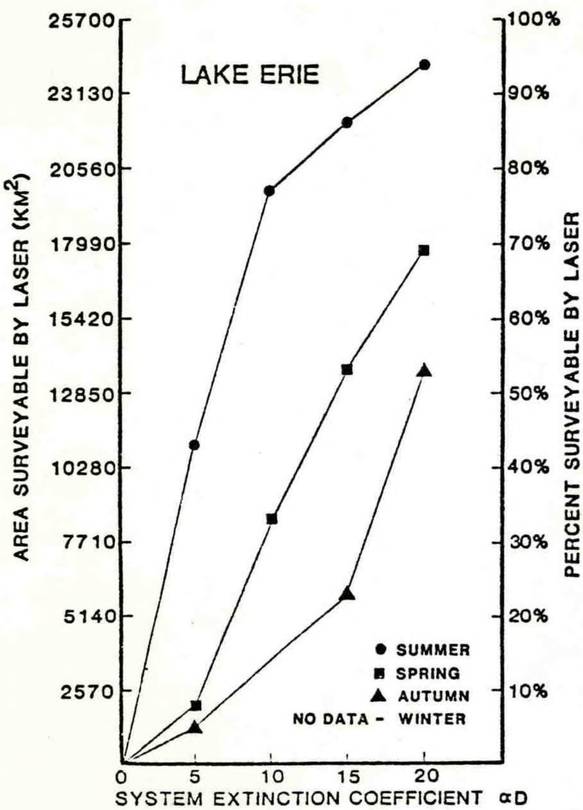


Figure 19. Gulf of Mexico (one section north of Tampa Bay) - chart of estimated laser surveyable area for $\alpha D = 20$.



LOCATION	- LAKE ERIE
CHART USED FOR DEPTHS	- 14820
CHART SCALE	- 1:400,000
TOTAL AREA	- 25,700 KM^2
TYPE OF DATA	- DISCRETE MEASUREMENTS
NUMBER OF DATA STATIONS	- SPRING - 525 SUMMER - 651 AUTUMN - 441 WINTER - 45
AVERAGE DATA STATION DENSITY	- SPRING - 1 PER 49 KM^2 SUMMER - 1 PER 40 KM^2 AUTUMN - 1 PER 58 KM^2 WINTER - 1 PER 572 KM^2
TIME SPAN OF DATA	- SPRING - 1967-78 SUMMER - 1967-78 AUTUMN - 1967-75 WINTER - 1969-78
OPTICAL PARAMETERS MEASURED	- JACKSON TURBIDITY UNITS, SOME SECCHI DEPTHS
RANGE OF MONTHLY MEAN WATER LEVELS	- -0.22 TO +1.5 METERS AROUND 1955 LOW WATER DATUM OF CHART 14820
EFFECT ON SURVEYABILITY OF TIDES/WATER LEVEL	- -1 1/2%
TYPICAL MAX DEPTH SURVEYABLE	- 18 METERS
CONFIDENCE IN ESTIMATES	- LOW

Figure 20. (upper left) Lake Erie - estimated laser surveyable area at 1955 low water datum

Table 9. (upper right) Lake Erie - supporting data for laser surveyability estimate

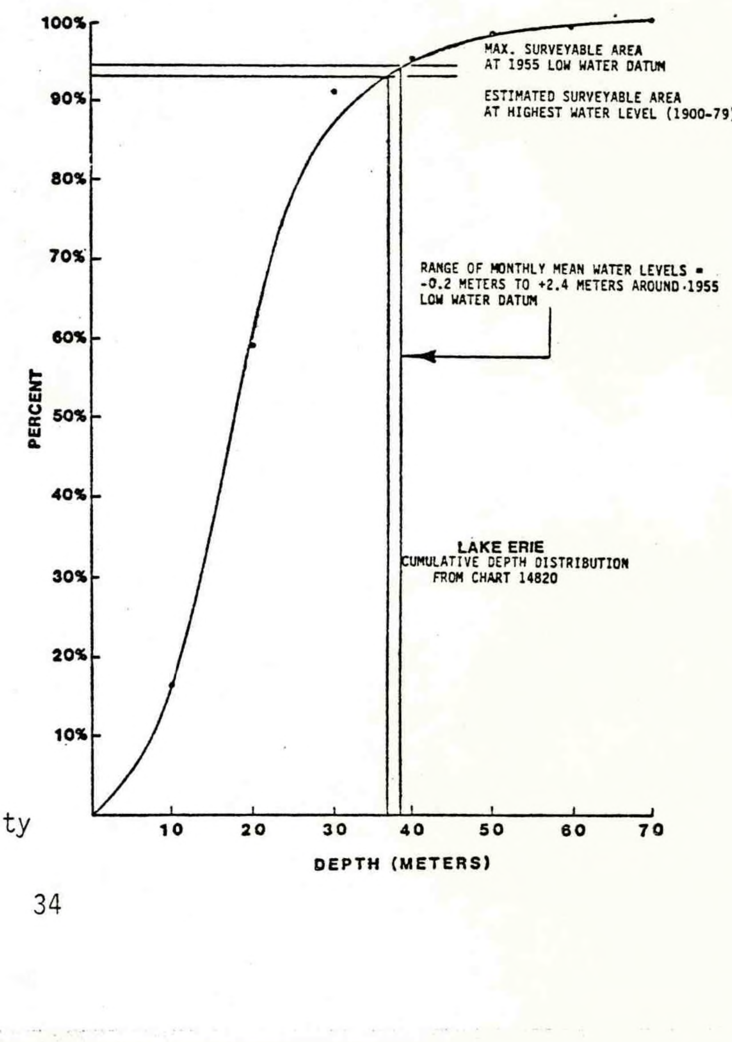


Figure 21. (lower right) Lake Erie - effect of water level on surveyability estimate

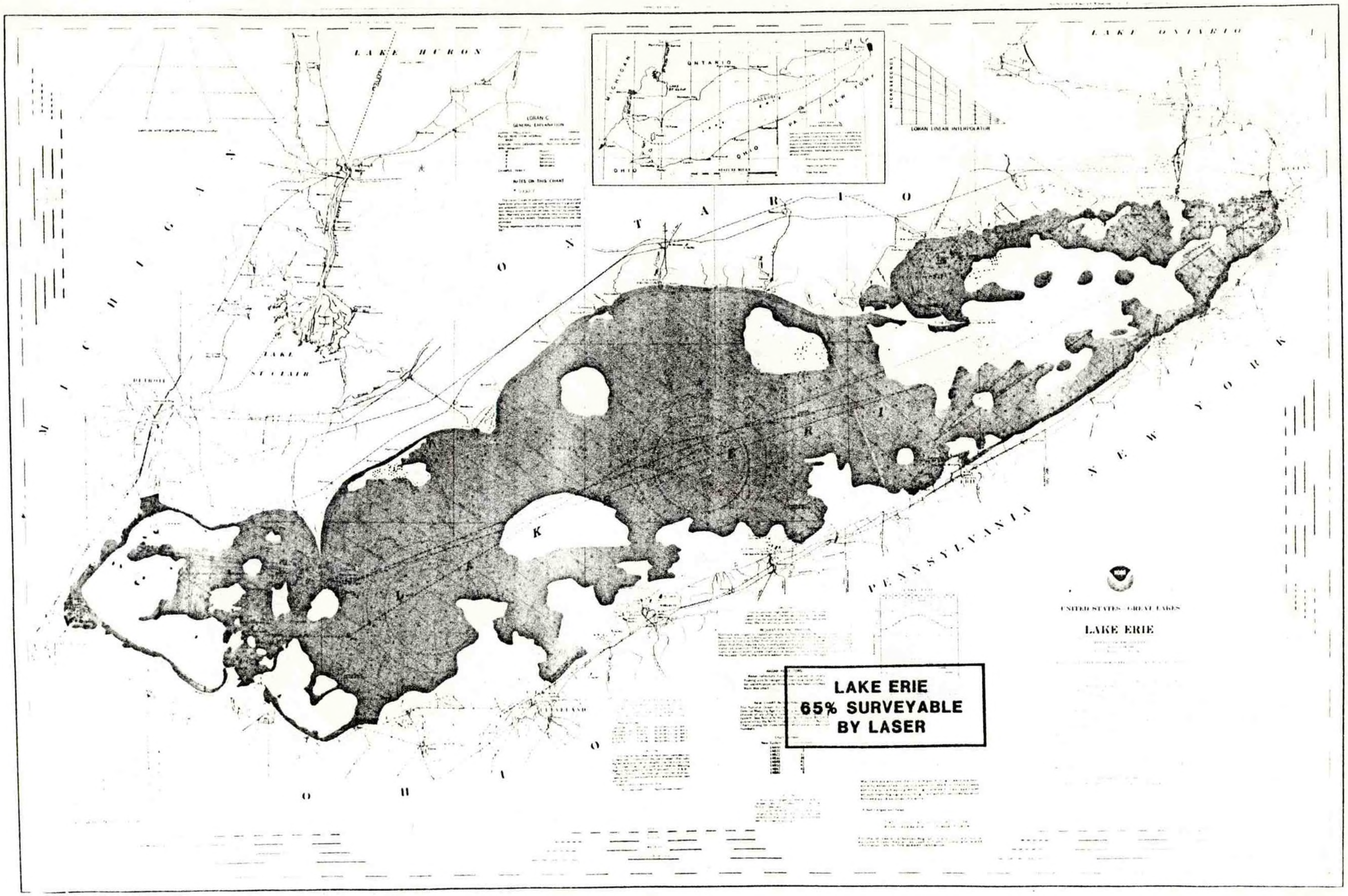
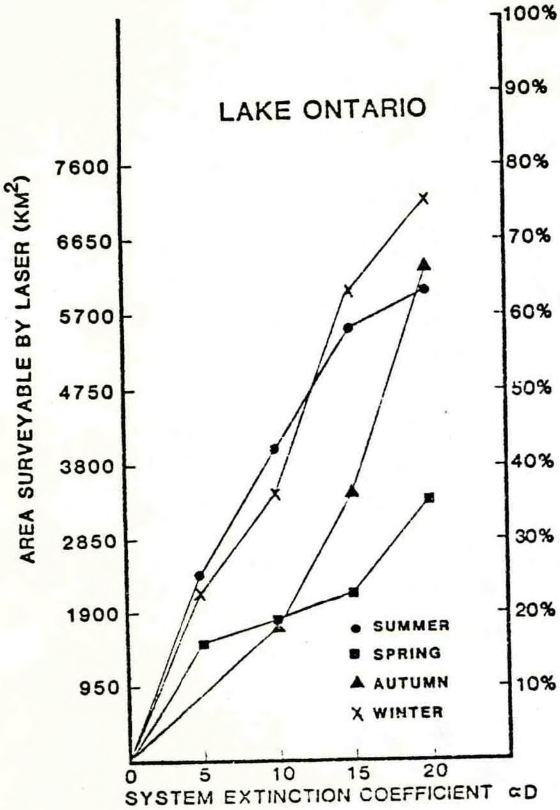


Figure 22. Lake Erie - chart of estimated laser surveyable area for $\alpha D = 20$.



LOCATION	- LAKE ONTARIO
CHART USED FOR DEPTHS	- 14800
CHART SCALE	- 1:400,000
TOTAL AREA	- 19,000 KM^2
TYPE OF DATA	- DISCRETE MEASUREMENTS
NUMBER OF DATA STATIONS	- SPRING - 417 SUMMER - 510 AUTUMN - 360 WINTER - 116
AVERAGE DATA STATION DENSITY	- SPRING - 1 PER 47 KM^2 SUMMER - 1 PER 38 KM^2 AUTUMN - 1 PER 54 KM^2 WINTER - 1 PER 168 KM^2
TIME SPAN OF DATA	- SPRING - 1966-69, 70-71, 74-76 SUMMER - 1966-71, 73-76 AUTUMN - 1967-71, 73-76 WINTER - 1970-73
OPTICAL PARAMETERS MEASURED	- JACKSON TURBIDITY UNITS, SOME SECCHI DEPTHS
RANGE OF MONTHLY MEAN WATER LEVELS	- -0.15 TO +1.9 METERS AROUND 1955 LOW WATER DATUM OF CHART 14800
EFFECT ON SURVEYABILITY OF TIDES/WATER LEVEL	- -1%
TYPICAL MAX DEPTH SURVEYABLE	- 8-11 METERS
CONFIDENCE IN ESTIMATES	- LOW

Figure 23. (upper left) Lake Ontario - estimated laser surveyable area at 1955 low water datum

Table 10. (upper right) Lake Ontario - supporting data for laser surveyability estimate

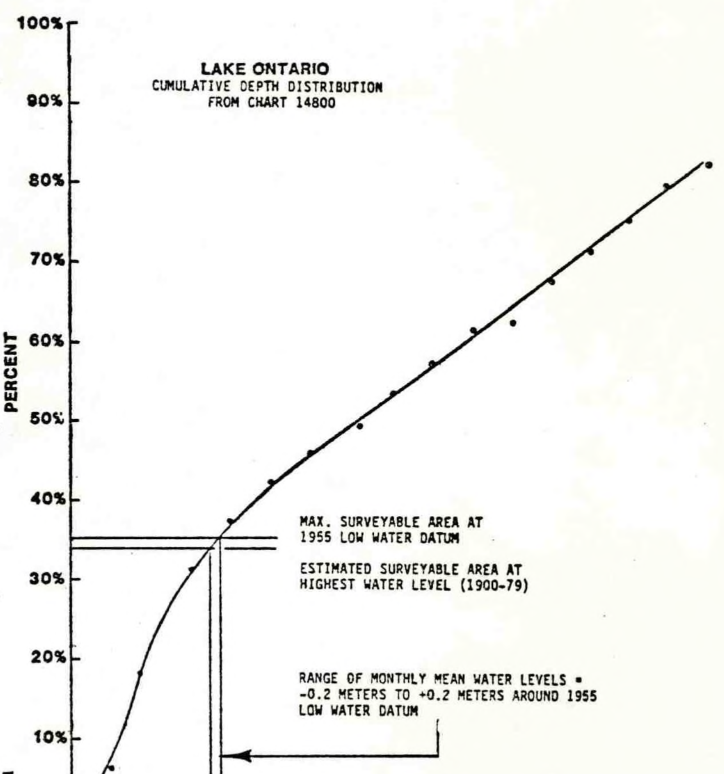


Figure 24. (upper right) Lake Ontario - effect of water level on surveyability estimate

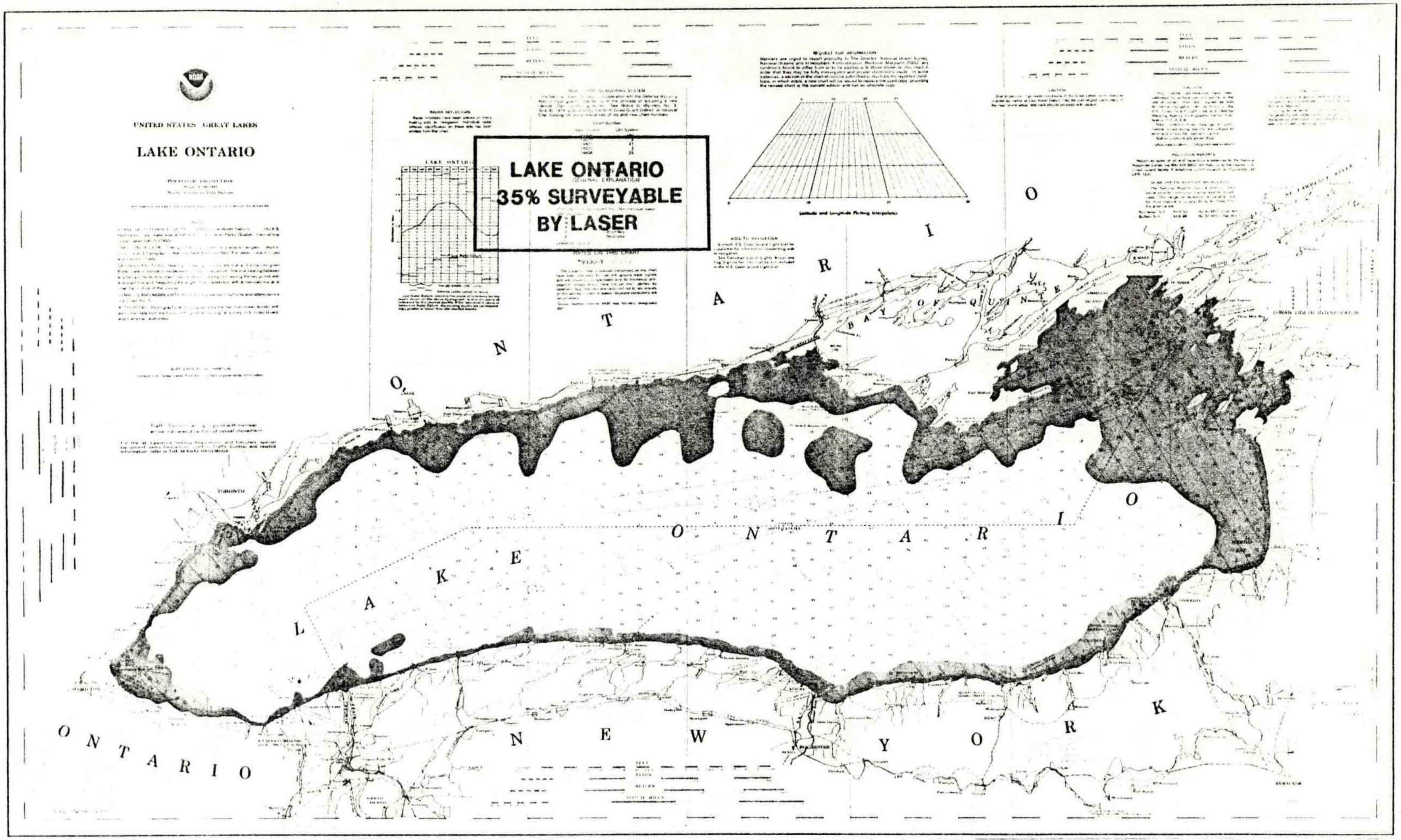
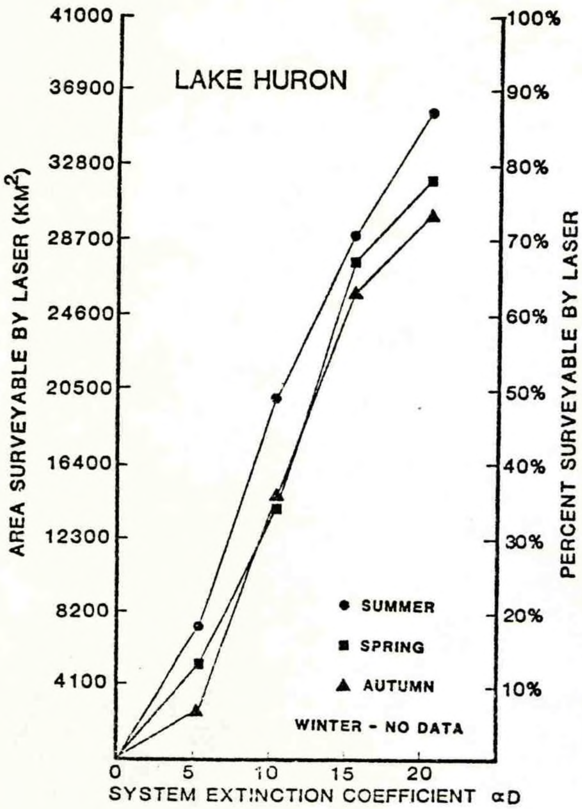


Figure 25. Lake Ontario - chart of estimated laser surveyable area for $\alpha D = 20$.



LOCATION	- LAKE HURON
CHART USED FOR DEPTHS	- 14860
CHART SCALE	- 1:500,000
TOTAL AREA	- 41,000 KM^2
TYPE OF DATA	- DISCRETE MEASUREMENTS
NUMBER OF DATA STATIONS	- SPRING - 218 SUMMER - 201 AUTUMN - 153 WINTER - 23
AVERAGE DATA STATION DENSITY	- SPRING - 1 PER 273 KM^2 SUMMER - 1 PER 296 KM^2 AUTUMN - 1 PER 389 KM^2 WINTER - 1 PER 2,585 KM^2
TIME SPAN OF DATA	- SPRING - 1970-76 SUMMER - 1968-75 AUTUMN - 1968, 70-72, 74-75 WINTER - 1974
OPTICAL PARAMETERS MEASURED	- JACKSON TURBIDITY UNITS, SOME SECCHI DEPTHS, SOME FORMAZINE TURBIDITY UNITS
RANGE OF MONTHLY MEAN WATER LEVELS	- -0.4 TO +1.3 METERS AROUND 1955 LOW WATER DATUM OF CHART 14860
EFFECT ON SURVEYABILITY OF TIDES/WATER LEVEL	- -1%
TYPICAL MAX DEPTH SURVEYABLE	- 35 METERS
CONFIDENCE IN ESTIMATES	- LOW

Figure 26. (upper left) Lake Huron - estimated laser surveyable area at 1955 low water datum

Table 11. (upper right) Lake Huron - supporting data for laser surveyability estimate

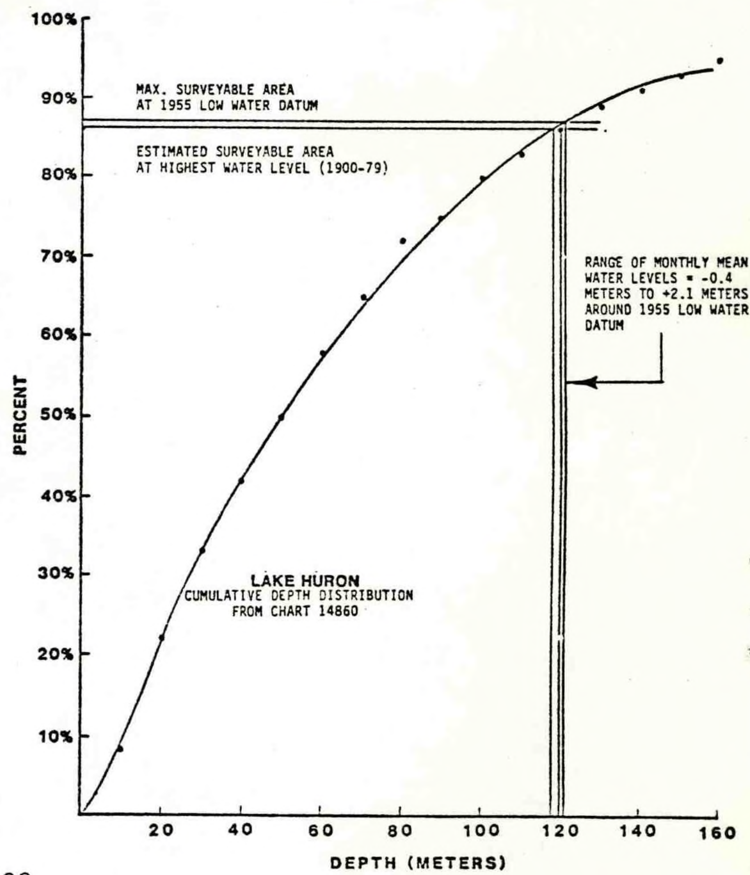


Figure 27. (lower right) Lake Huron - effect of water level on surveyability estimate

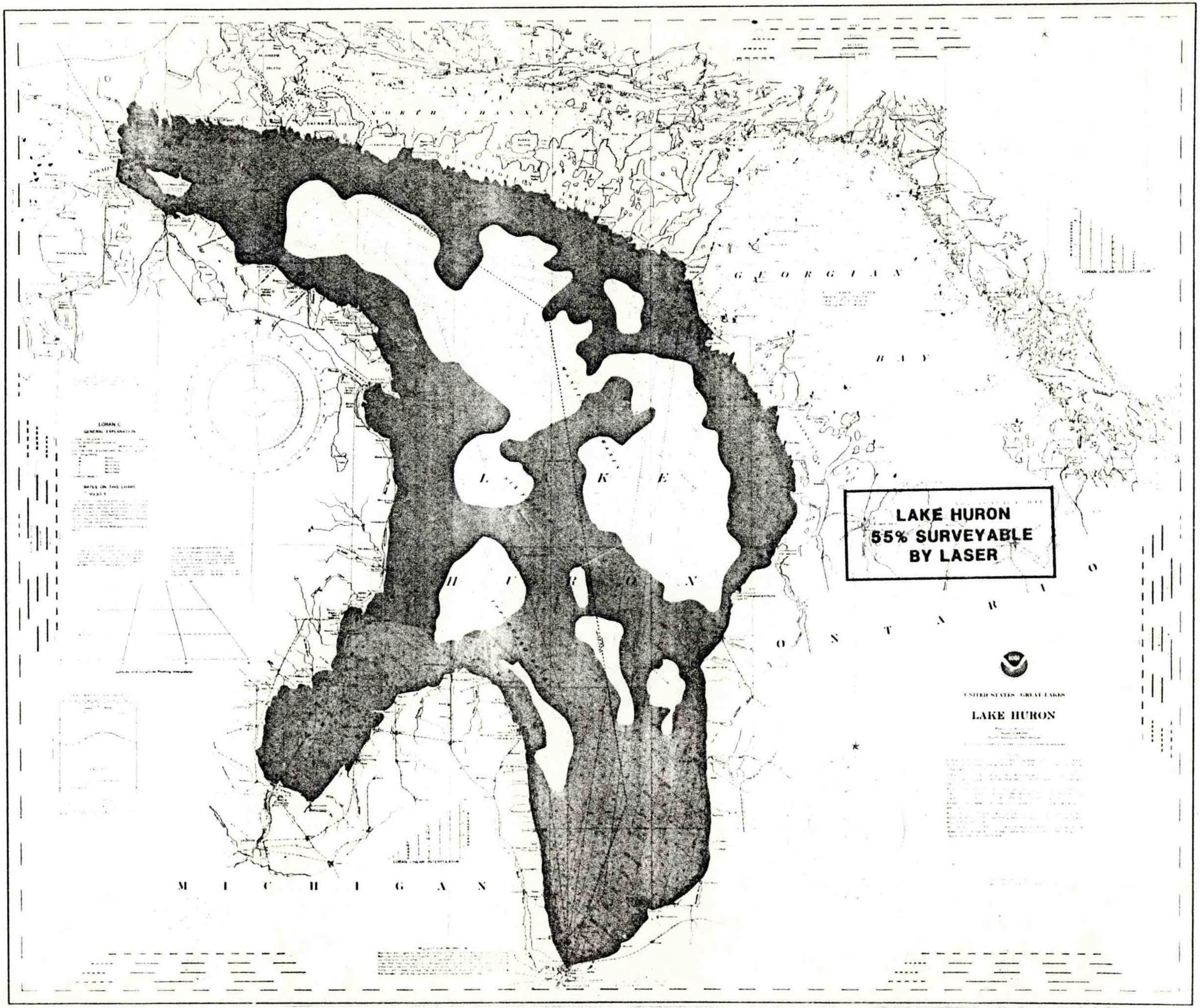
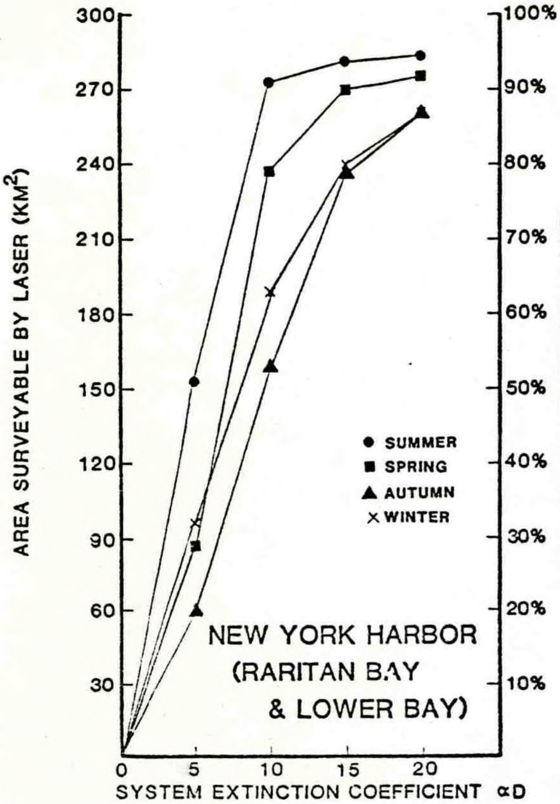


Figure 28. Lake Huron - chart of estimated laser surveyable area for $\alpha D = 20$.



LOCATION	- NEW YORK HARBOR (RARITAN BAY AND LOWER BAY)
CHART USED FOR DEPTHS	- 12327
CHART SCALE	- 1:40,000
TOTAL AREA	- 300 KM^2
TYPE OF DATA	- DISCRETE MEASUREMENTS AND AERIAL PHOTOGRAPHS
NUMBER OF DATA STATIONS	- SPRING - 42 SUMMER - 33 AUTUMN - 26 WINTER - 32
AVERAGE DATA STATION DENSITY	- SPRING - 1 PER 7 KM^2 SUMMER - 1 PER 9 KM^2 AUTUMN - 1 PER 12 KM^2 WINTER - 1 PER 9 KM^2
TIME SPAN OF DATA	- SPRING - 1965-74, 77-78 SUMMER - 1966-72, 76-77 AUTUMN - 1964-73, 76-77 WINTER - 1965-74, 77
OPTICAL PARAMETERS MEASURED	- JACKSON TURBIDITY UNITS, SOME SECCHI DEPTHS
MEAN RANGE OF TIDES	- 2.4 METERS
EFFECT ON SURVEYABILITY OF TIDES/WATER LEVEL	- -8.5%
TYPICAL MAX DEPTH SURVEYABLE	- 7 METERS
CONFIDENCE IN ESTIMATES	- LOW

Figure 29. (upper left) New York Harbor (Raritan Bay and Lower Bay) - estimated laser surveyable area at mean low water

Table 12. (upper right) New York Harbor (Raritan Bay and Lower Bay) - supporting data for laser surveyability estimate

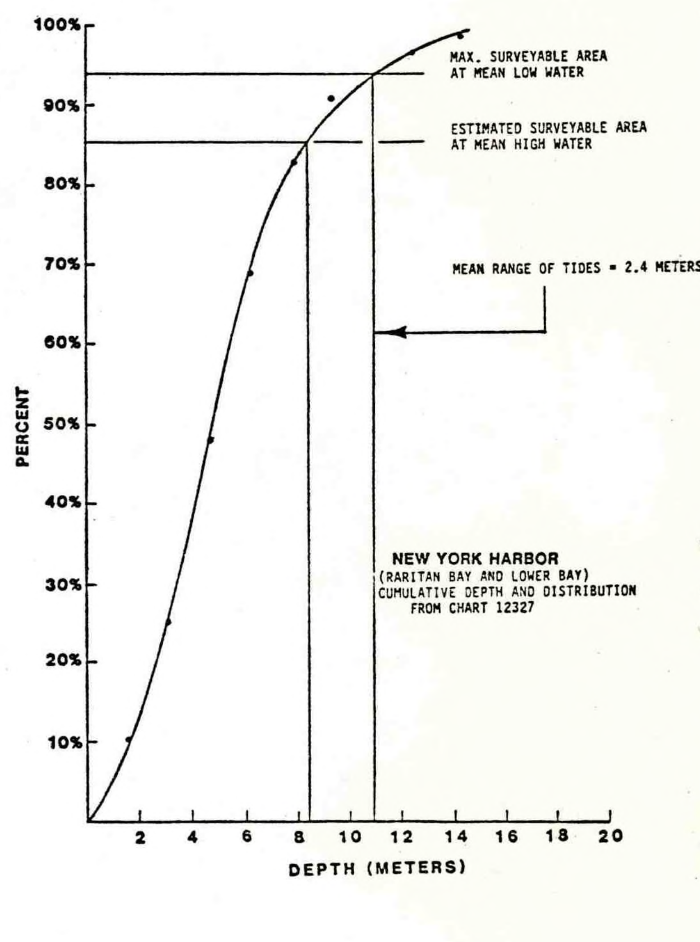


Figure 30. (lower right) New York Harbor (Raritan Bay and Lower Bay) - effect of tides on surveyability estimate

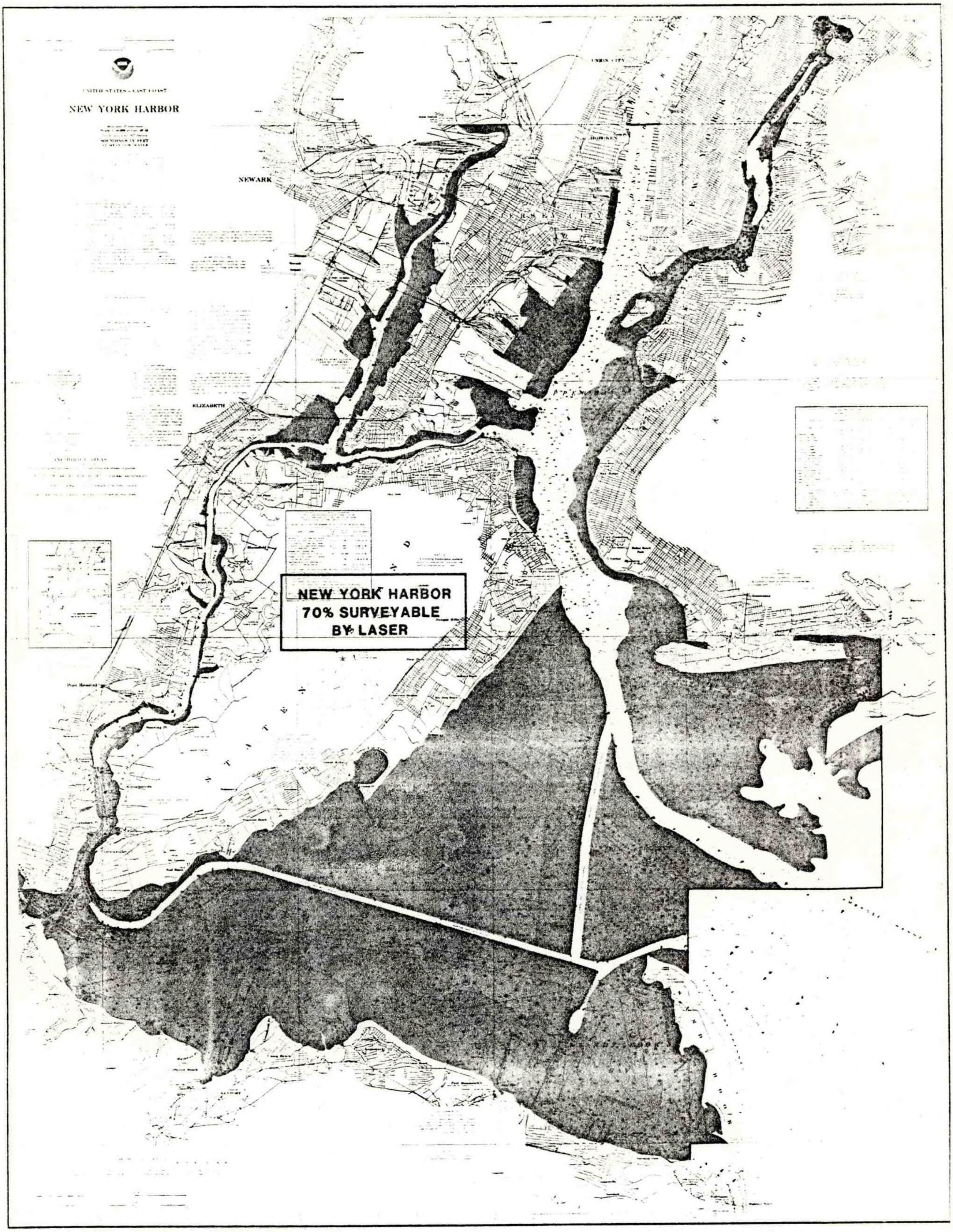


Figure 31. New York Harbor (Raritan Bay and Lower Bay) - chart of estimated laser surveyable area for αD = 20.

APPENDIX A

Data Sources

The following are the sources of data that were used in this study. Also included are the persons contacted, and the format of the data.

(1) Environmental Protection Agency (STORET). Contact was made with Mr. P. Lindenstruth (FTS 426-7792) for types of data that were available. Six water clarity parameters were selected (e.g., Jackson Turbidity Units and Secchi) and were searched for in the East Coast and Gulf of Mexico data bases. Data were to include estuary and nearshore stations. Four magnetic tapes of data (mostly in the Jackson Turbidity Units) were acquired from the STORET. The data were annotated as to location, time, sampling organization, depth of sample, etc.

(2) Georgia Department of Natural Resources. Contact was made with Mr. Maxwell Walker (404-656-4905) of the Georgia Department of Natural Resources. Copies of four reports prepared by the U.S. Army Corps of Engineers and Brunswick Junior College were secured. The data consisted of 875 data points for eleven stations along the coast of Georgia.

(3) United States National Oceanographic Data Center. Contact was made with Mr. Robert Gelfield (FTS 634-7298) of the USNODC Data Retrieval Section. Arrangements were made to collate data from the one degree latitude-longitude squares closest to the shoreline for the East, West, and Gulf Coasts. The data stations were scrutinized so as to include only those stations with water depths of less than fifty feet. The water clarity was expressed as Secchi

depth. Two hundred thirty data points were taken from the total data set. USNODC is one of the major repositories for oceanographic data, but most data stored are from deep water stations.

(4) Smithsonian Institution. A report published in 1960 by the Smithsonian includes approximately four hundred observations of Secchi readings taken along the East Coast from Nova Scotia to the Florida Keys. Each station was sampled four times per year (once per season) with most stations being close to shore. The paper is found in the Smithsonian Miscellaneous Collections Vol. 139, Number 10 ("Water Transparency Observations Along the East Coast of North America," Williams, Johnson, & Dyer).

(5) Washington Analytical Services Center, EG&G (formerly Wolf Research and Development Corporation). A data search was done by this EG&G company in October 1974 outlining data collected by organizations which had done sampling in the Chesapeake Bay. The report was prepared for the State of Maryland's Department of Natural Resources in conjunction with its Power Plant Siting Program. More than 350,000 samples are recorded taken at 4300 different stations. Data span the time between 1939 and 1974 with fourteen organizations contributing data to the base.

APPENDIX B

Conversion Formulae for Measures of Water Clarity

PARAMETERS	UNITS	RELATIONSHIP	FOOTNOTE
Secchi disk reading in inches, s	α in m^{-1}	$\alpha = 180.3/S - 0.55$	1, 8
Secchi disk reading in meters, s	α in m^{-1}	$\alpha = 4.58/S - 0.55$	8
Jackson Turbidity Units, JTU	α in m^{-1}	$\alpha = 0.065 + 0.256(JTU)$	2
Percent Transmission, %T	α in m^{-1}	$\alpha = \{1/d\} \{\ln(100/\%T)\}$	3, 4
Formazine Turbidity Units, FTU	α in m^{-1}	$\alpha = 0.065 + 0.256(FTU)$	5
Suspended Sediments, L	α in m^{-1}	$\alpha = 0.42L$	6, 7

1. α is the beam attenuation coefficient.
2. Swenson, W., Influence of Turbidity on Fish Abundance in Western Lake Superior; EPA Report 600/3078-067; Environmental Research Laboratory, Duluth, Minn., 55804. Swenson's expression relates FTU and the suspended sediment load, L. $\alpha = 0.42L$ was then used to convert L to α. Swenson's measurements were for fresh water. The effect of assuming the same relationship for salt water is unknown.
3. d is the path length in meters.
4. This is from the definition of percent transmission $\%T = 100 \exp(-\alpha d)$.
5. Since FTU and JTU represent about the same type of measurement, the assumption was made that the expressions which convert to α would be the same.
6. L is the suspended sediment load in milligrams per kilogram.

7. The relationship between suspended sediment load, L, and α was taken from Biggs, 1968*, using Schubels' 1968** data for the median particle diameter of 1.56 μm. Biggs gives $\alpha = (0.657/d)L$ which, with $d = 1.56$ μ m, gives $\alpha = 0.42L$.

8. Using a reasonably small set of data (n = 26), a relationship between α and the Secchi disc reading (S) was developed as part of this study:

$$\alpha = \frac{4.58}{S} - 0.55 \quad \text{(A)}$$

This relationship was used in determining α for this study. Recently a larger set of data (n = 362) has been uncovered. These data are related by:

$$L = 9.9/S - 0.28 \quad \text{(B)}$$

with a correlation coefficient of 0.938.

When this is combined with $\alpha = 0.42L$ (see 2. above), one gets

$$\alpha = \frac{4.16}{S} - 0.12 \quad \text{(C)}$$

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*Biggs, R. B., 1968, "Optical grain size of suspended sediment in upper Chesapeake Bay," Chesapeake Science, p.9, 251-266.

**Schubel, J. R., 1969, "Size distribution of the suspended particles of the Chesapeake Bay turbidity maximum," Netherlands Jour. of Sea Research, 4, p. 283-309.

Within the range of α values normally found in Chesapeake Bay, eqs. (A) and (C) give values than are reasonably close as may be seen by the table below:

Secchi disc reading (m)	α by (A)	α by (C)
0.5	8.61	8.20
1.0	4.03	4.04
2.0	1.74	1.96
3.0	0.98	1.27

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