Feasibility of Dual Mode Lidar for Pelagic Fish Surveys

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Executive Summary

The purpose of this final report is three-fold: first, to review the results of tests conducted by Science Application International Corporation (SAIC); second, to show how these results might be applied to fisheries applications; and finally, to describe the best direction for the technology in an R&D and commercial market. A brief summary of these points follows.

The SAIC lidar field test conducted at the NRaD TRANSDEC tank in San Diego resulted in fish identification at a depth of 76 feet in turbid water with $K = 0.147^{-m}$ (this corresponds to 205-foot depths in blue water where $K = 0.055^{-m}$). The test also distinguished between tuna and swordfish, but not between like species such as bluefin and yellowfin tuna. Fish detection depth exceeded 109 feet (294 feet for blue water) and data extrapolation showed it to be possible to 450 feet (in blue water). Analysis of current fish behavior data shows that for detection and identification of yellowfin tuna, for instance, the detection system must exceed 150feet during daylight hours and average 300 feet for a likely probability of detection. These results indicate that lidar systems may have some application in pelagic fisheries research, but that tools for routine areal surveys will require further development.

Comparison of lidar vs. passive systems such as hyperspectral imaging yields interesting results. Lidar enables detection to depths approximately twice as deep as are possible with hyperspectral systems (passive systems will not detect deeper than 150 feet in blue water), has comparable resolution, has better than an order of magnitude greater search volume per exposure due to its natural spread with depth, and comparable power and size requirements. Its most probable commercial application would be for deployment on fish-spotting helicopters flying from ocean fleets.

The hardware subcomponents used in the field test were 3-5 years old. Newer technology is less expensive and more sensitive. A hardened prototype capable for helicopter deployment and test could be built with confidence in less than one year for under $200,000. Production systems could be built for 60% of this price. These systems could be assembled with an open framework to allow for further R&D development. In particular, the most interesting application would be to combine hyperspectral and lidar. Using the fluorescence signatures of fish, there is strong evidence that "like species" (yellow and bluefin tuna) fish may be differentiated at depths greater than 300 feet by their dissimilar colors (fluorescence).

The systems are feasible for commercial development and sale if the price could be held under $300,000. These systems would also allow for further development as a tool for the R&D developer at the university for open ocean studies. With the open architecture, small changes to the system could make it a powerful ocean chemistry analysis system. The dual use of the system is readily apparent.

Program Objectives

This was a proof-of-principle experiment necessary to determine the feasibility of an airborne lidar sensor for surveying large pelagic fish in the upper layer of the ocean. The overall objective was to determine conditions in which pelagic fish may be detected and identified using airborne laser devices (i.e., detection and identification vs. depth and clarity of water).

Potential Applications

A number of potential applications for lidar as a research tool can be imagined. In the short term, the system could be used for surveillance of shallow, swordfish-targeted, longline deployments and verification of logsheet catch reports. It may also be used for studies of fish distribution in relation to oceanographic features such as temperature fronts and eddies. In the long term, lidar may be used for studies of dynamics of tuna school formation, for aerial surveys of large scale fish distribution, and for estimation of population size. We believe the detection and volume/mass assessment of fish spawning areas are another potential research application. Researchers at the University of Hawaii have used fluorescence for detection and Raman scattering for identification of sample fish eggs in the laboratory.[1] A literature survey shows a growth in the number of published lidar papers over the last few years.[2,3,4,5,6] This is due to a growing awareness of the possibilities of lidar as a tool, as well as the developments in the performance of subcomponents of the lidar system as well.

As a commercial tool, we have identified a number of applications for an affordable, lightweight, low power consuming lidar system including (but not limited to) large fish school location, detection, and identification using a helicopter mount from tuna fish fleets. It has been proposed that locating a single tuna school that would have otherwise gone undetected would pay for the lidar system. For bluefin tuna schools found in south Australia, there has been considerable interest from CSIRO.[7]

Interest in Lidar

There are a number of active research developments in the field of lidar including a single commercial venture. NOAA's 1995-2005 strategic plan calls for support for "additional system development and field testing of laser-based LIDAR to assess fish populations or count individuals."[8] John Hunter from NMFS and Jim Churnside from Environmental Technology Laboratory led an Airborne Fishery Assessment Technology Workshop in March, 1994[9] with 21 participants. Summarizing the conference, the general recommendations for lidar included use for improving existing indices of abundance for small, schooling pelagic fishes and bluefin tuna; developing a biomass measurement system for small, schooling pelagic fishes; and developing a fisheries-hydrography system for studying the ecology and forecasting the distribution and movements of large epiplagic fishes such as oceanic salmon and tunas. Hunter has also recently finished a tour of operation incorporating his own lidar system. This system uses a double and

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[1] Sharma, S.K., R. Gauldie, C. Schoen, PACON Australia, 1993.

[2] Menzies, R.T., "Airborne CO_2 Coherent Lidar Measurements of Cloud Backscatter and Opacity over the Ocean Surface," Journal of Atmospheric and Oceanic Technology 11(3), 6/94, 770.

[3] Churnside, J.H., "Ocean Optics-Effect of Penetration Depths and Swell-Generated Tilt on Delta-K Lidar Performance," Applied Optics 33(12), 4/94, 2363.

[4] Palmer, A.J., "Delta-k-Lidar Sensing of the Ocean Surface," Applied Optics 31(21), 7/92, 4275.

[5] Bunkin, O.A., "Stratification of the Coefficients at Attenuation of Laser Light in the Upper Ocean as Indicated by Lidar Sounding Data," DOKLADY 312(3), 5/90, 292.

[6] Weinman, J.A., "Derivation of Atmospheric Extinction Profiles and Wind Speed over the Ocean from a Satellite-Borne Lidar," Applied Optics 27(19), 10/88, 3994.

[7] CSIRO workshop, Hobart Tasmania, Nov. 1992.

[8] 1995-2005 Strategic Plan, NOAA, July 15,1993, PII-1-19

pulsed YAG laser to operate at 532 nm and uses a photomultiplier tube (PMT) for detection only. His system is limited to detection only and at depths of 20 to 30 meters.

NOAA recently published a report describing their lidar system.[10] In it they describe their use of a frequency-doubled YAG laser detection-only system with ability to detect tuna as deep as 17 meters. The primary motivation for their lidar is described as being a method of locating tuna when they are not associated with dolphins. Because 60-90% of the annual eastern tropical Pacific tuna catch is due to dolphin indicator cues, this method is intended to eliminate incidental dolphin mortality. A simple system, their detection scheme is similar to that of John Hunter in that they use a PMT.

Kaman Aerospace, Inc. (Tucson, AZ) has what is believed to be the first lidar system for sale or lease. It incorporates a diode-pumped, frequency-doubled YAG laser and an ICCD detector. The system has not found a great deal of success. This can be attributed to its high purchase and lease price, heavy physical weight and large power consumption that limit it to airplane use only, and limited sensitivity resulting from its shadow image detection scheme.

System Description

Active/Imaging Lidar

Lidar is an acronym for **li**ght **d**etection **a**nd **r**anging. In its simplest design, a short pulse of laser light is directed toward the target. A receiver pointed in the same direction waits for a return signal reflected from the target. The return of the signal indicates the presence of a target, and the elapsed time indicates its range (refer to Fig. 1). As opposed to the "Hunter" type lidar systems, SAIC uses an intensified and gated charge-coupled diode (ICCD) detector to "image" or take pictures of the target. The ICCD is made up of an intensifier, a coupled fiber-optic bundle, and a silicon based CCD with fast frame, transfer electronics to enable it to operate at a real-time rate of 30 Hz. In comparing the ICCD image capturing system to a PMT-based system like Hunter's lidar system it is much like comparing CCD-based multichannel spectroscopy to the old scanning monochrometers with a PMT. There is no comparison. Referring to Fig. 1, note that the SAIC has both a PMT and ICCD in the beam return. A fraction of the return signal is directed to the PMT while the majority of it is directed toward the ICCD. When the PMT begins to detect a return above a particular threshold, it triggers the ICCD to capture the image with a "5 ns" slice (or approximately 5 feet) depth resolution. This is termed "dual-mode lidar" for which SAIC has been awarded a patent (#5,270,780). Note that the system may operate in both "imaging" and "shadow" mode. Imaging mode would be one in which the gating of the ICCD is set for the exact time that the reflected photons from the target are returned. If the ICCD were triggered to capture an image any time after the target reflection, the image captured would be one in which a shadow of the target would be surrounded by scattering in the ocean. Since ocean scattering can be many orders of magnitude less in intensity than reflected photons from a target, the contrast on a shadow image generally suffers greatly when compared to a reflective target. For the Kaman lidar system, their system operation is to run on shadow mode

[9] Hunter, J.R., J.H. Churnside, "Airborne Fishery Assessment Technology, A NOAA Workshop Report, Administrative Report LJ-95-02, Feb. 1995.

[10] Oliver, C.W., "Development of an Airborne Lidar System to Detect Tunas in the Eastern Tropical Pacific Purse-

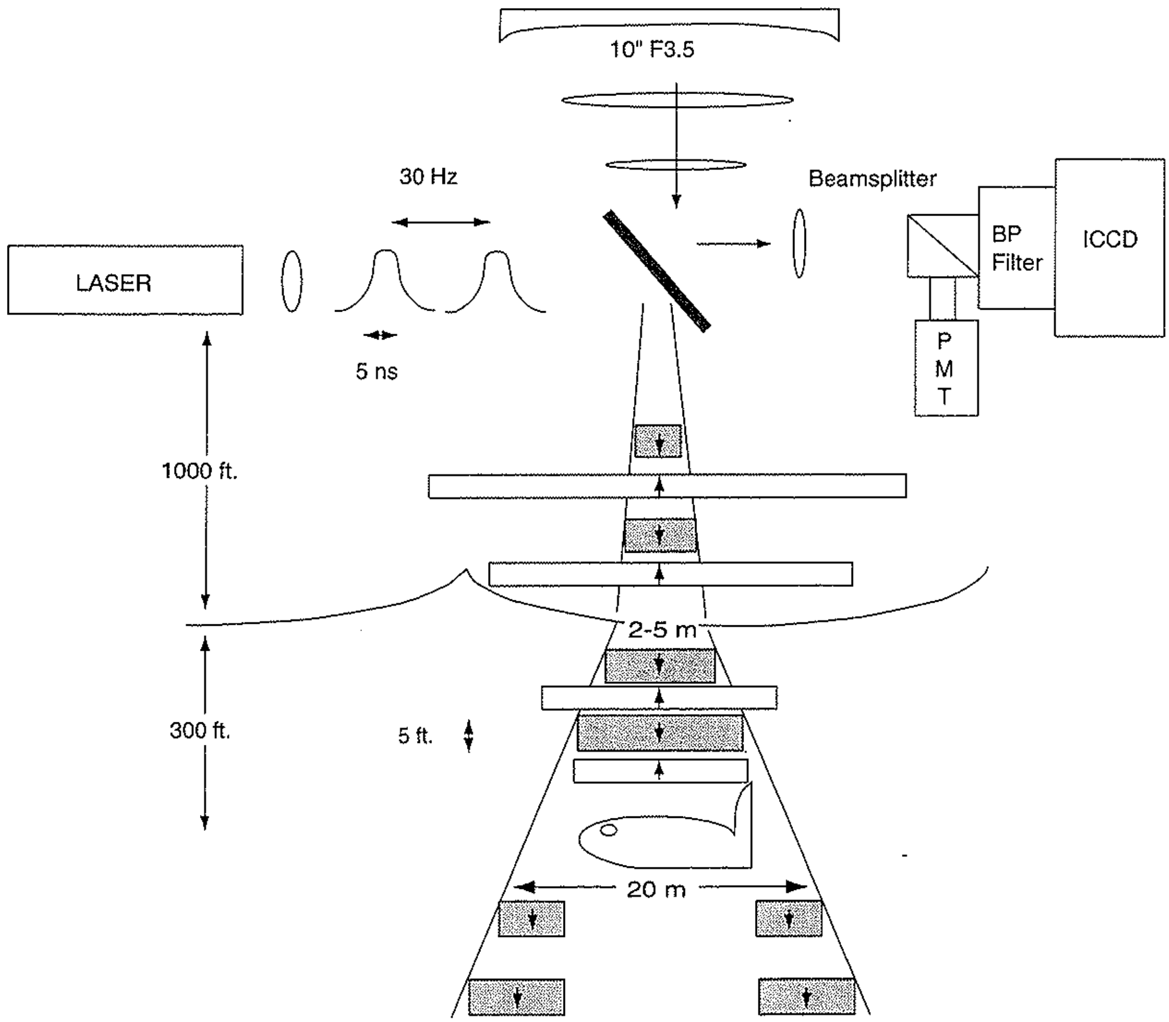


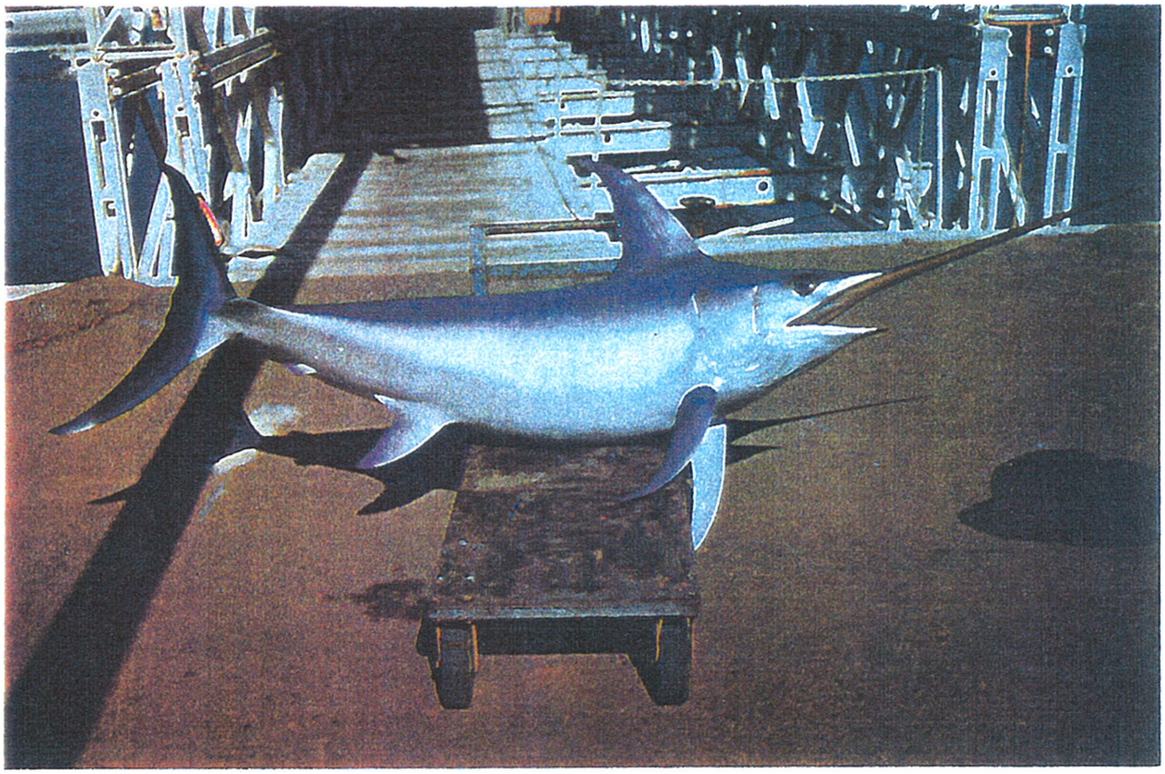
Fig. 1. Dual mode lidar.

in order that they may trigger their camera at the same depth with each shot. Consequently, their system lacks fidelity when compared to the SAIC system presented here.

Test Procedures and Data

The K value for the water at the NRaD facility was measured to be 0.147^{-m}.[11] This corresponds to an attenuation length (AL) of 6.8 m, or termed 6.8 m water. Typical open ocean water has a $K = 0.055^{-m}$, corresponding to 18.2 m water. Consequently, the test water was very turbid when compared to open ocean water, but allowed for placement of targets at >33 m, which simulated the target depth in blue ocean water to be >88 m. The laser was a frequency-doubled YAG operating at 532 nm, 75 mJ per pulse, with a 15 Hz repetition rate. The beamspread was 6 ft in diameter at 11.5 m depth. Four targets were fabricated by Lyons & O'Haver, Master Taxi-

[11] Attenuation length = 1/K. An attenuation length is the distance in the ocean where the signal loss due to scattering in the water is 1-1/e, or 63%. For lidar, losses in attenuation lengths are $(1\text{-}1/e)^2$ since the return signal must always propagate the same distance back.



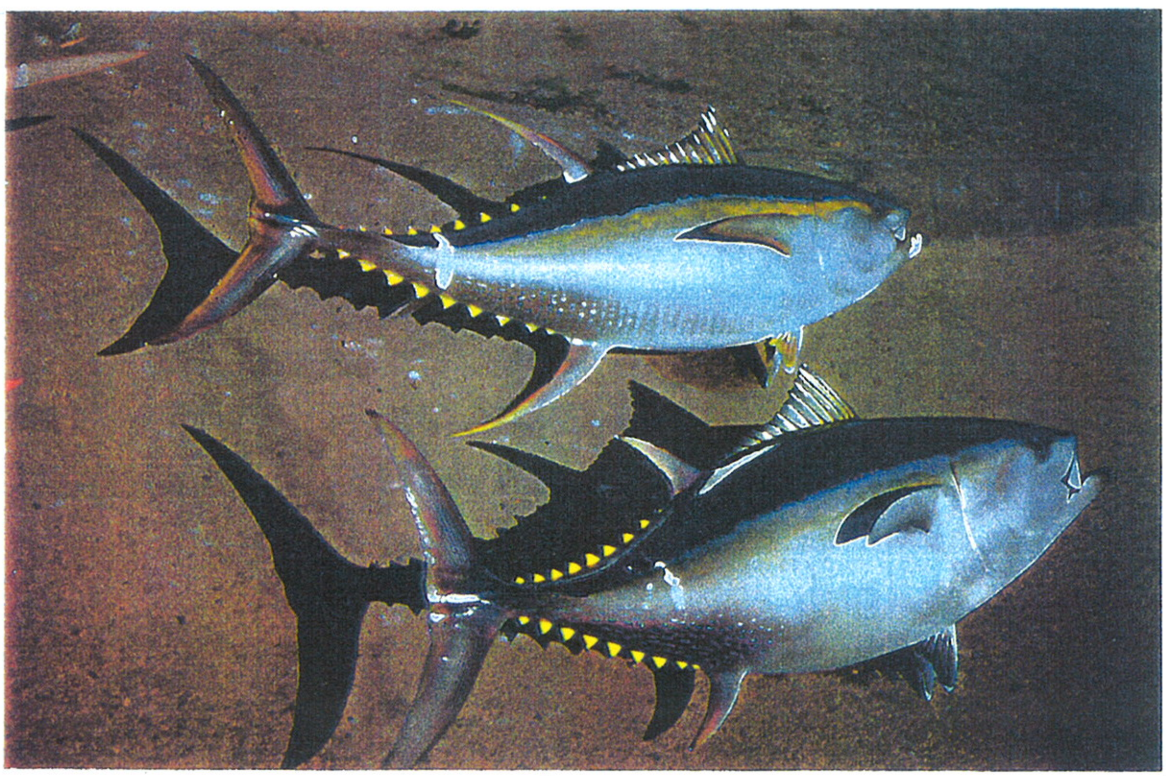


Fig. 2. Three of four fabricated fish targets. Top photo shows broadbill #2, bottom photo shows yellowfin tuna (top) and bluefin tuna (bottom).

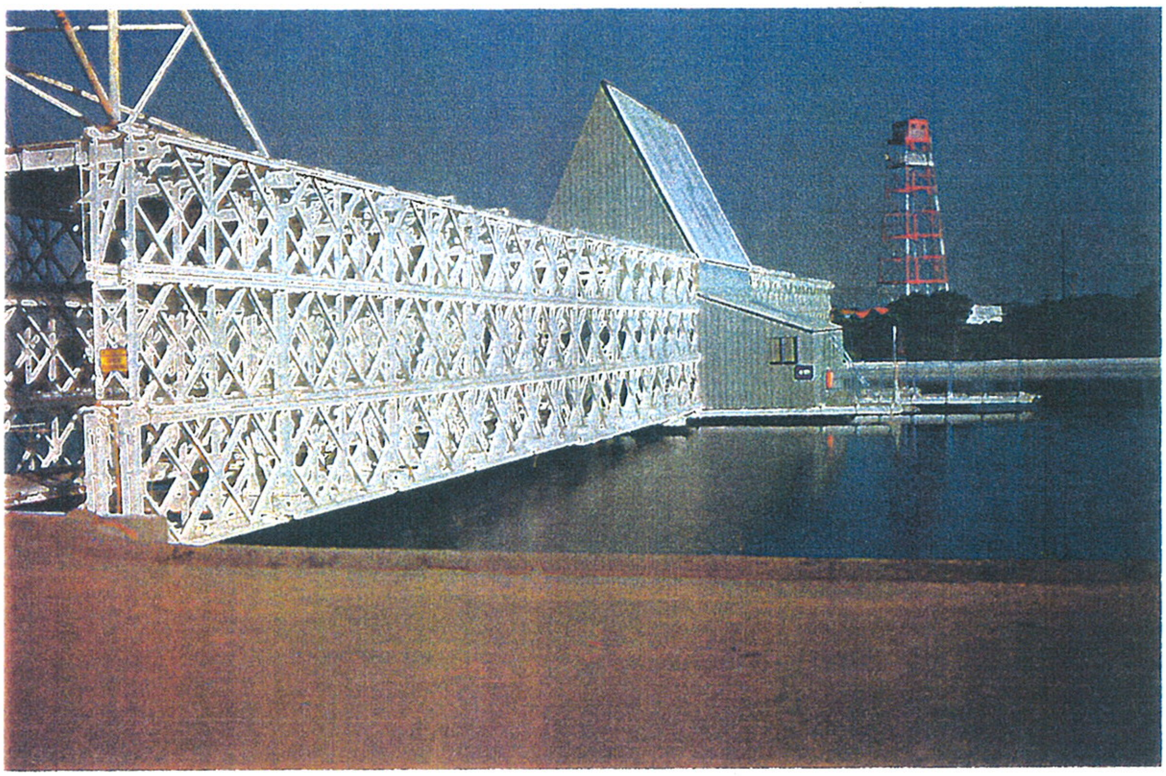
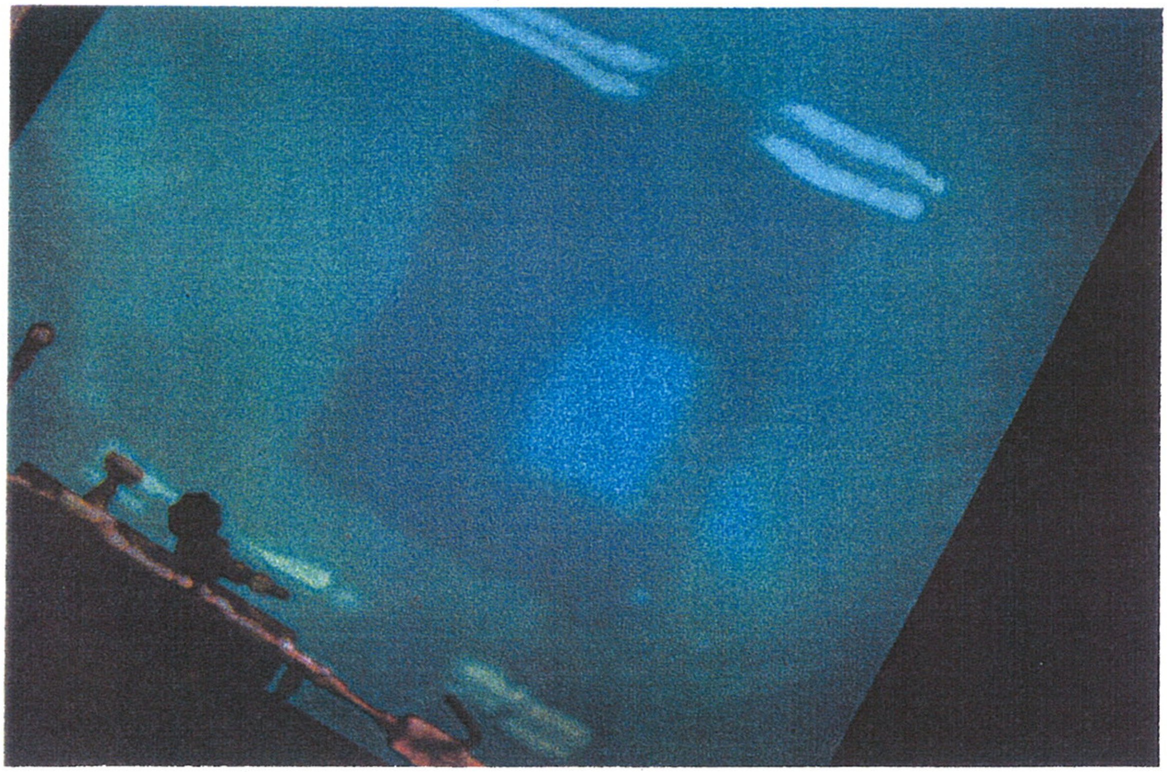


Fig. 3. Test site at NRaD TRANSDEC facility.

Fig. 4. Photo of mirror placed on bottom of tank (top). Schematic representation of mirror to increase path length (bottom).



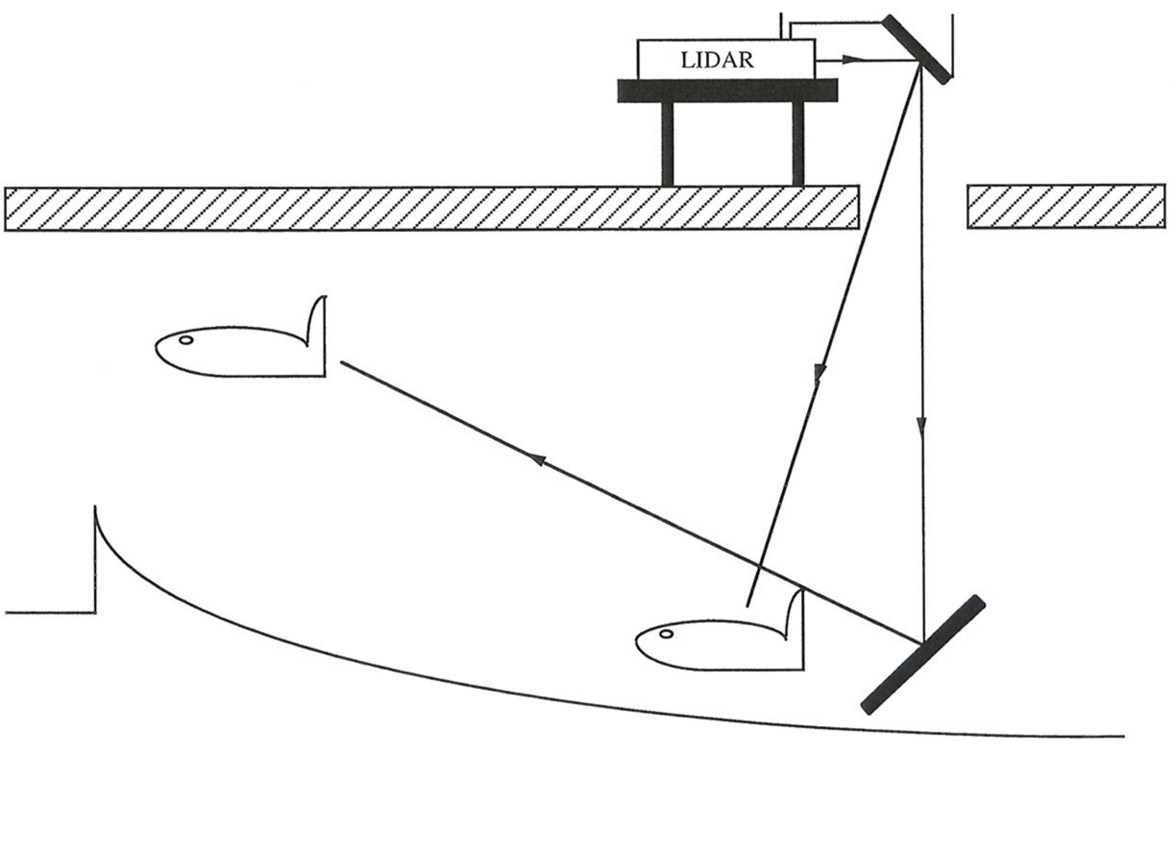


Fig. 4. Photo of mirror placed on bottom of tank (top). Schematic representation of mirror to increase path length (bottom).

dermists, 8180 Parkway Dr., La Mesa California 92041 (619) 697-3217. These fish are shown in Fig. 2 and consist of the following:

Yellowfin Tuna	212 lb.	77" long
Bluefin Tuna	175	68"
Broadbill #1	312	120"
Broadbill #2	125	101"

These fish were hollow fiberglass replicas created in molds made from live fish. They were painted to simulate these fish as they looked alive in the water. The fact that our own human eyes are registering the reflection (as a function of wavelength) of the fish, and since the lidar works solely by reflection, and because these fish appear in color and shape to be real, then they are valid targets to evaluate the lidar. In the future, if fluorescence is to be measured, then these fish will not be suitable targets. Wood and steel inserts were fabricated on which mounts were made to maneuver the fish once under water.

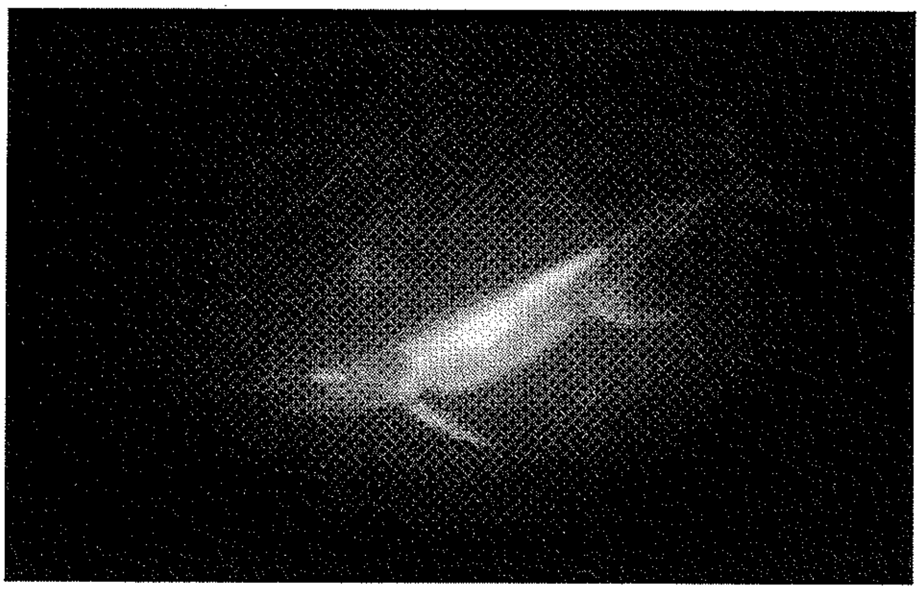


Fig. 5. Broadbill #1, 76 ft. in NRaD tank (corresponding to 205 ft. in blue water) side view.

The NRaD tank was 40 ft deep and 250 ft in diameter. The dock facility is positioned over the center of the tank and is shown in Fig. 3. The lidar was directed down into the tank and fish were positioned at the bottom of the tank and at the edges of the tank. When the fish were placed at the edges of the tank, a 6-ft diameter mirror was placed at the bottom of the tank to direct the light to the target (refer to Fig. 4).

Results

In order not to be too redundant with the SAIC report, a few images have been selected to show the results here. Figure 5 shows an image taken of broadbill #1 at a depth corresponding to

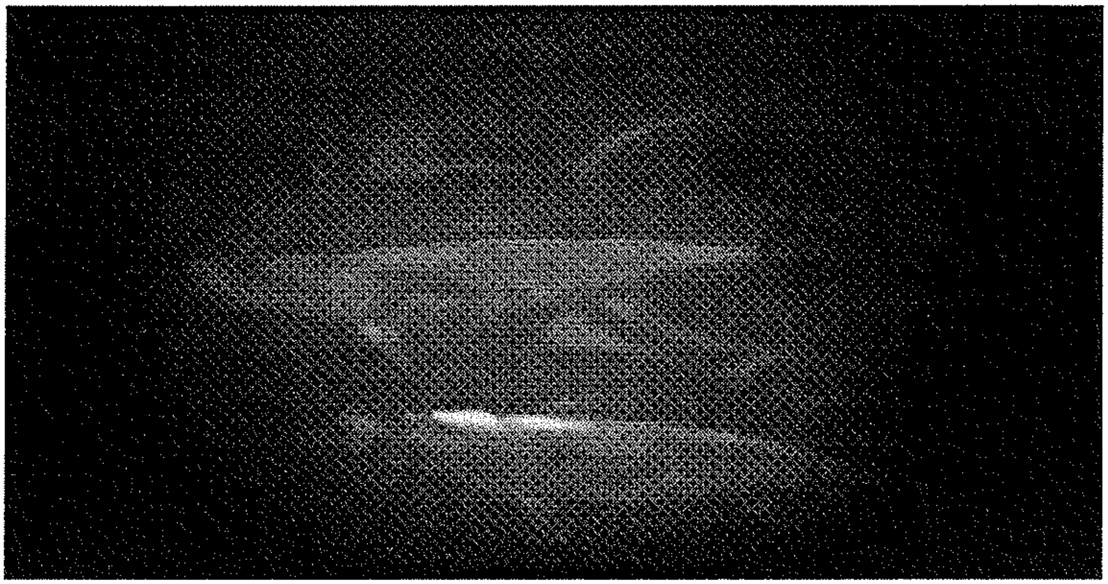


Fig. 6. Yellowfin and bluefin tuna, 40 ft. in NRaD tank (corresponding to 106 ft. in blue water) side view.

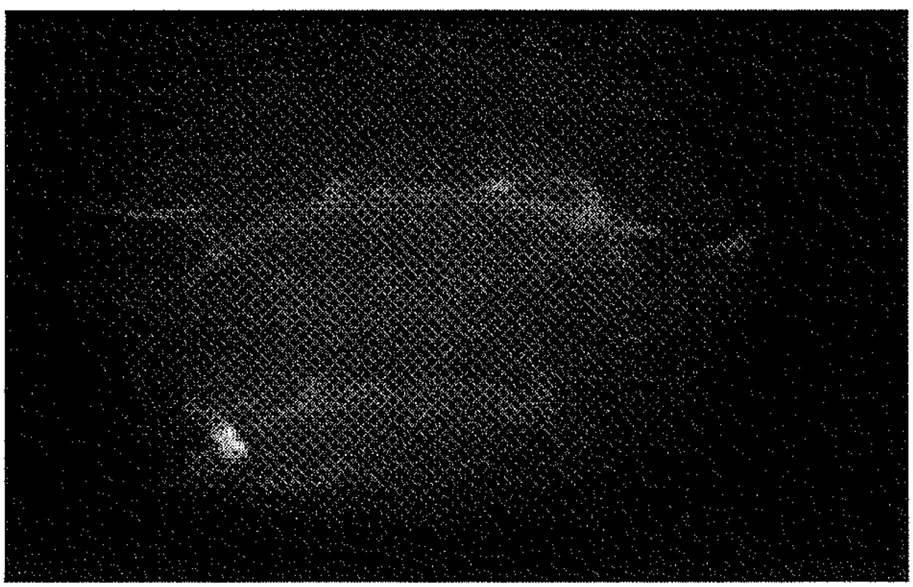


Fig. 7. Yellowfin and bluefin tuna, 40 ft. in NRaD tank (corresponding to 106 ft. in blue water) top view.

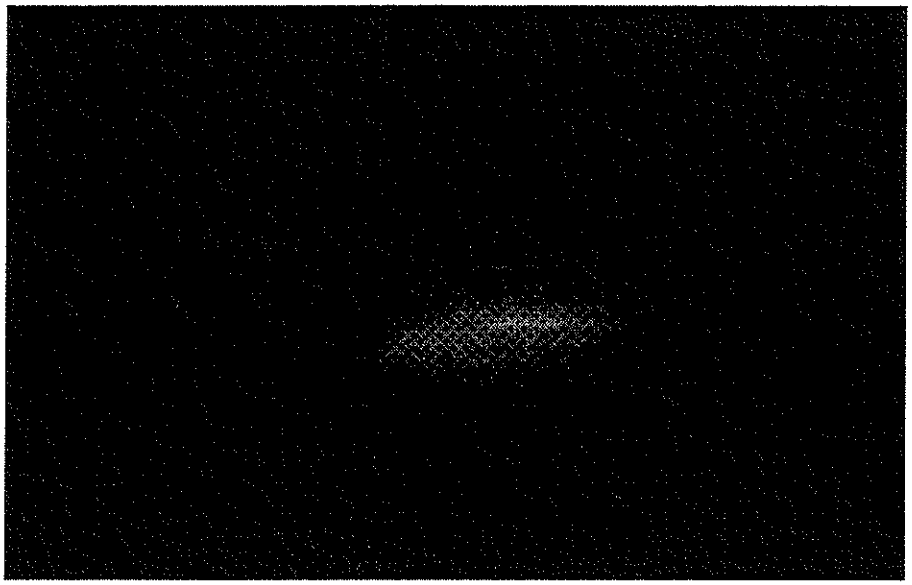


Fig. 8. Yellowfin tuna, 110 ft. in NRaD tank (corresponding to 294 ft. in blue water).

205 ft in open water; the fish is tilted at 90 degrees. Figure 6 shows both tuna placed at 90 degrees in 106-ft-deep open water. Figure 7 shows the same two tuna, placed at 0 degrees (top view) in 106-ft-deep open water. Figure 8 shows the yellowfin tuna placed at 294-ft-deep open water.

Analysis of Results

Comparing Figs. 5 and 6, it is clear that at 205-ft depths, one can see shapes well enough to distinguish between broadbill and tuna species. However, from Fig. 6 it is difficult if not impossible to tell the bluefin and yellowfin apart. In fact, it is hard when they are not in water. Figure 7 shows the difficulty in imaging the fish directly from the top. This is reasonable since fish colorings are a camouflage for predators. Bottoms and sides of fish are known to be at least 80% reflective while the tops are less than 20%.[12] This is apparent in the images. Fish have a dorsal light response, which allows them to maintain their back perpendicular to the downwelling radiance, thereby maintaining a tilt angle close to 0 degrees under most daytime conditions. However, on clear days with a low sun angle, fish close to the surface may lean toward the light. Likewise, at night, active lidar may be most sensitive since the dorsal light response of fish are weak or absent.[13] Finally, fish in schools do not normally all swim at 0 degrees, and furthermore, the lidar may be directed at a 25-degree incidence, reducing the depth by only 10% (refer Fig. 9). Figure 8 provides a nice detection limit on which fish may be detected.

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[12] Fredericksson, K., "Underwater laser-radar experiments for bathymetry and fish-school detection," Goteborg Institute of Physics Report, GIPR-162, pg. 28, 1978.

[13] Aoki, I., "Photographic observations on the behavior of Japanese anchovy at night in the sea," Mar. Ecog. Ser. 43:213-221, 1988.

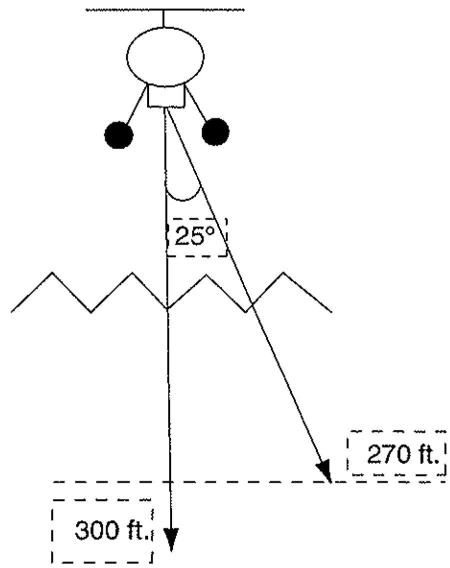

Fig. 9. Simple procedure to illuminate more reflective sides of fish.

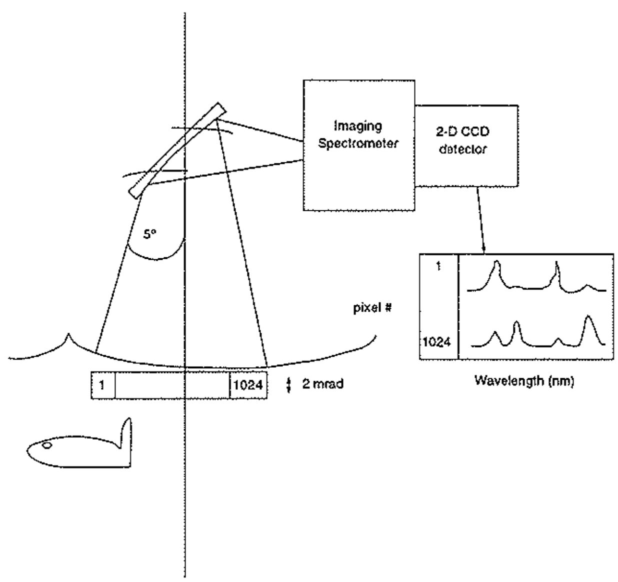

Fig. 10. Hyperspectral line scanning mode of operation.

The most critical parameter in evaluating lidar tests is laser spot size vs. depth. A very narrow beam will enable deeper penetration into the ocean but reduce the sampling area. Furthermore, safety is a concern. At the surface of the water, the spot size should adjust the 100 mJ per pulse to average 1 $\mu J/cm^2$. This is corresponds to a 3-m spot size at the surface. Optimally, a 20-m spot size would be desirable at a depth of 100 m. Tests here provided a 5-m spot at approximately 100 m. This reduces the photon budget by a factor of 4. However, with hardware available now, in particular new ICCD with new intensifier technology, this factor of four is compensated by the capability of this newer hardware.

Other types of detection systems

There are three classes of detection systems: airborne, including side-looking airborne radars (SLARs), synthetic aperture radars (SARs) and satellite; passive imaging, including simple video, multispectral and hyperspectral imaging; and active lidar which employs a laser source as described here. Airborne radar are not likely candidates for future research because they have no detection capabilities much past the surface of the water. Passive systems rely on the sun for illumination and obviously rely on it and calm waters for best results. Video yields no more information than an expert observer, but is repeatable for 2 to 3 ALs. Multispectral systems such as CASI rely on an imaging spectrograph and have improved detectability of schools to up to 3 ALs. However, no species-specific spectral characteristics of schools have been identified.

As opposed to multispectral systems that monitor a few wavelengths, hyperspectral systems monitor the entire visible spectrum. SETS Technology, Inc. (Mililani, HI) has found unprecedented success in its hyperspectral system. As opposed to the SAIC system that generates images from reflected photons generated by a source laser, the hyperspectral system generates images from reflected photons where the sun is the source. Through a "line scan" method, the hyperspectral system collects spectra from line images and stores them on the 2-D array of the CCD. As the plane flies, these line images are built on top of each other generating a composite frame (refer Fig. 10). Post-processing analysis using predefined spectral "signatures" indeed pulls images of interest from the background.

In April, 1995, SETS did a number of tests to analyze Kaneohe Bay bottom types (Fig. 11). The test was to see if hyperspectral imaging could discern between sandy and "lettuce type" bottoms along with identifying and mapping porities coral, montipora coral and mixed corals. Spectral signatures of each are shown in Fig. 12. The K value for Kaneohe Bay was 2 m and the depth ranged up to 3 ALs. Figure 13 shows the images after post-processing. Clearly, the system was able to detect, identify, and distinguish between bottom and coral types. Whereas it has always been believed that the strong attenuation of ocean water at non blue-green wavelengths restricted this type of development, SETS has truly shown otherwise.

Passive vs. Active

Which is better? Both have shown advantages. Comparing a number of properties of the two system leads to surprising results.

Table 1

	Active Lidar	Hyperspectral
Depth	6 ALs	3 ALs
Resolution	0.15 ft.	2 x 0.17 ft.
Swath Area	6 ft. diameter	180 x 2 ft. at surface
Power	+2 HP (laser)	+2 HP (computer)
Cooling	large fan available (helicopter)	
Weight	+30 lbs. (laser)	+30 lbs. (computer)
Processing	no	lots

•Depth

The difference between 6 ALs and 3 ALs is significant. Referring to Fig. 14, note the daytime and nighttime average depth for yellowfin tuna. When used at night, active lidar can cover the full depth cycle. Note also from Fig. 14 the volume of detection "per shot." Using the performance specifications from this test, and comparing these to the specifications given by SETS in their April 1995 Kaneohe Bay test, the difference in volume detection is almost an order of magnitude in favor of the active lidar. Although the spot size of the active lidar is small at the surface (6 ft diameter) and the hyperspectral system is considerably larger at 360 sq. ft. (2 x 180 ft), the hyperspectral detection volume is reduced as a function of depth due to the index of refraction change of the ocean water and due to the limited depth penetration. Active lidar has the advantage of natural ocean scattering with depth. Considering the most likely depth for desired fish is between 50 and 100 m, the system is optimized at this depth. Hyperspectral differs in image collection from active lidar in that it continuously builds images as quickly as the "plane" (in this case) can fly. However, active lidar relies on the repetition rate of its laser. Current affordable technology limits a laser that can put out 100 mJ per shot (optimal for this design for a depth penetration of 100 m) to 30 Hz. If mounted on a helicopter flying at 100 mph, the coverage rate overlaps at approximately a 20-m depth.

Again, assuming the application is big fish detection, this is optimized. For other applications such as fish egg detection and identification, this could be adjusted for better surface overlap without the depth penetration. Surface coverage and depth penetration are the tradeoffs that can be adjusted easily and on the fly. Kaman, Inc. invests a considerable amount of money for a diode-pumped, frequency-doubled YAG laser installed on their system to increase the repetition rate of their laser to a couple of hundred Hz so as to increase their swath width and thereby increase their coverage rate. In this fashion, the system may operate on a plane or may scan when mounted on a helicopter. It is interesting to refer to an article by Lo and Hunter.[14] Referring to Fig. 15, note that for the probability of detecting a fish school, increasing the swath width from a nonscanning laser of 2 m to a scanning system of 200 m has little or no effect. The driving force in school detectability is the chance encounter of the swath with an aggregation of schools; the width of the transect path that intersects such an aggregation is of negligible importance.

[14] Hunter and Lo, in preparation, 1995.

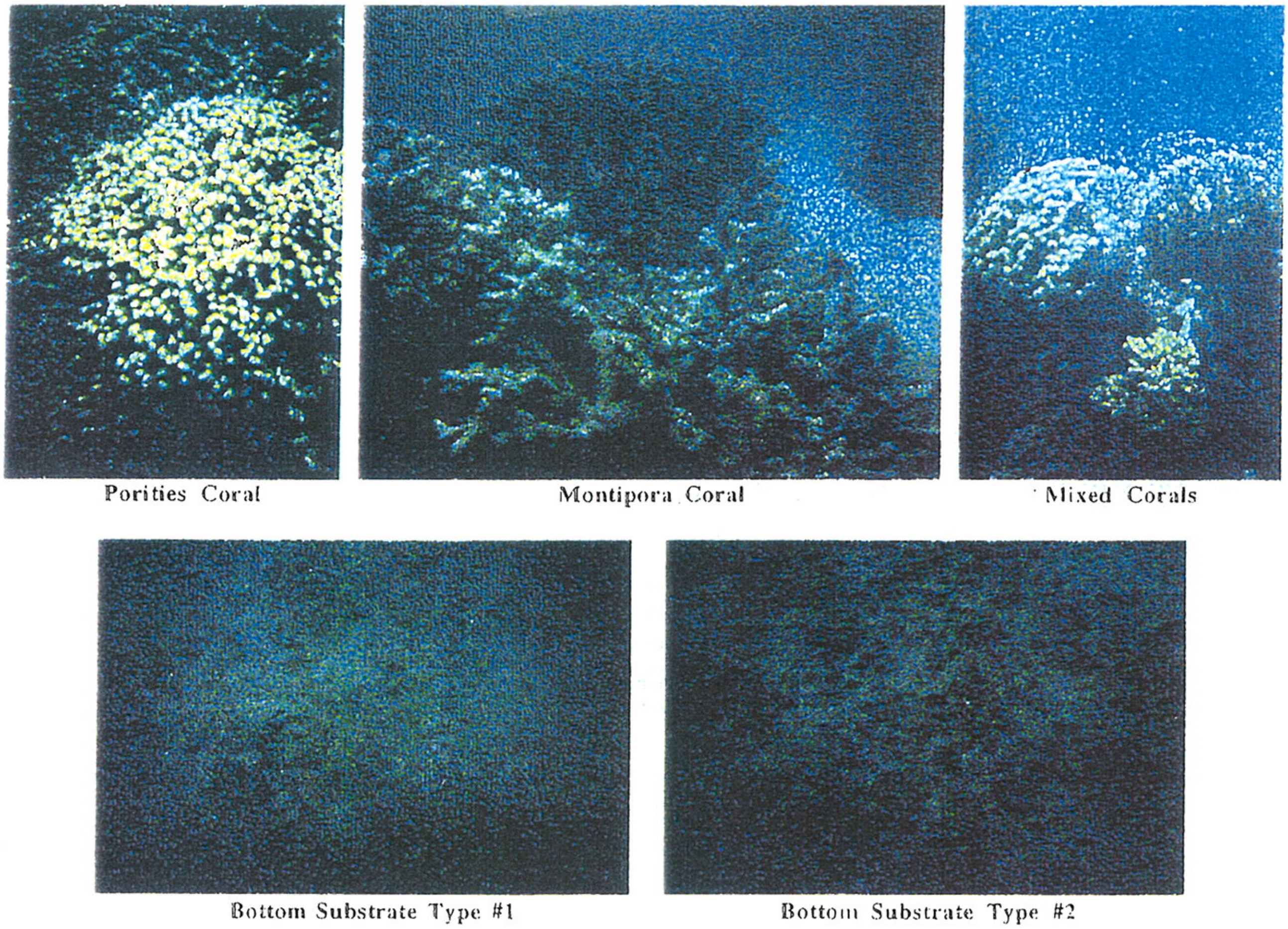

Fig. 11. Kaneohe Bay Bottom Types

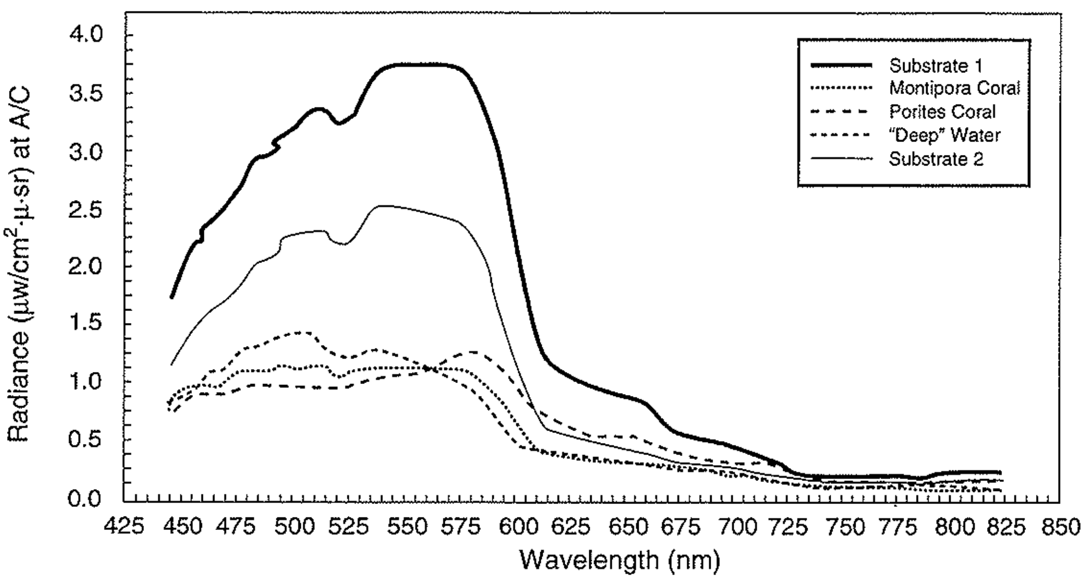

Fig. 12. Kaneohe Bay Endmember Radiance Spectra

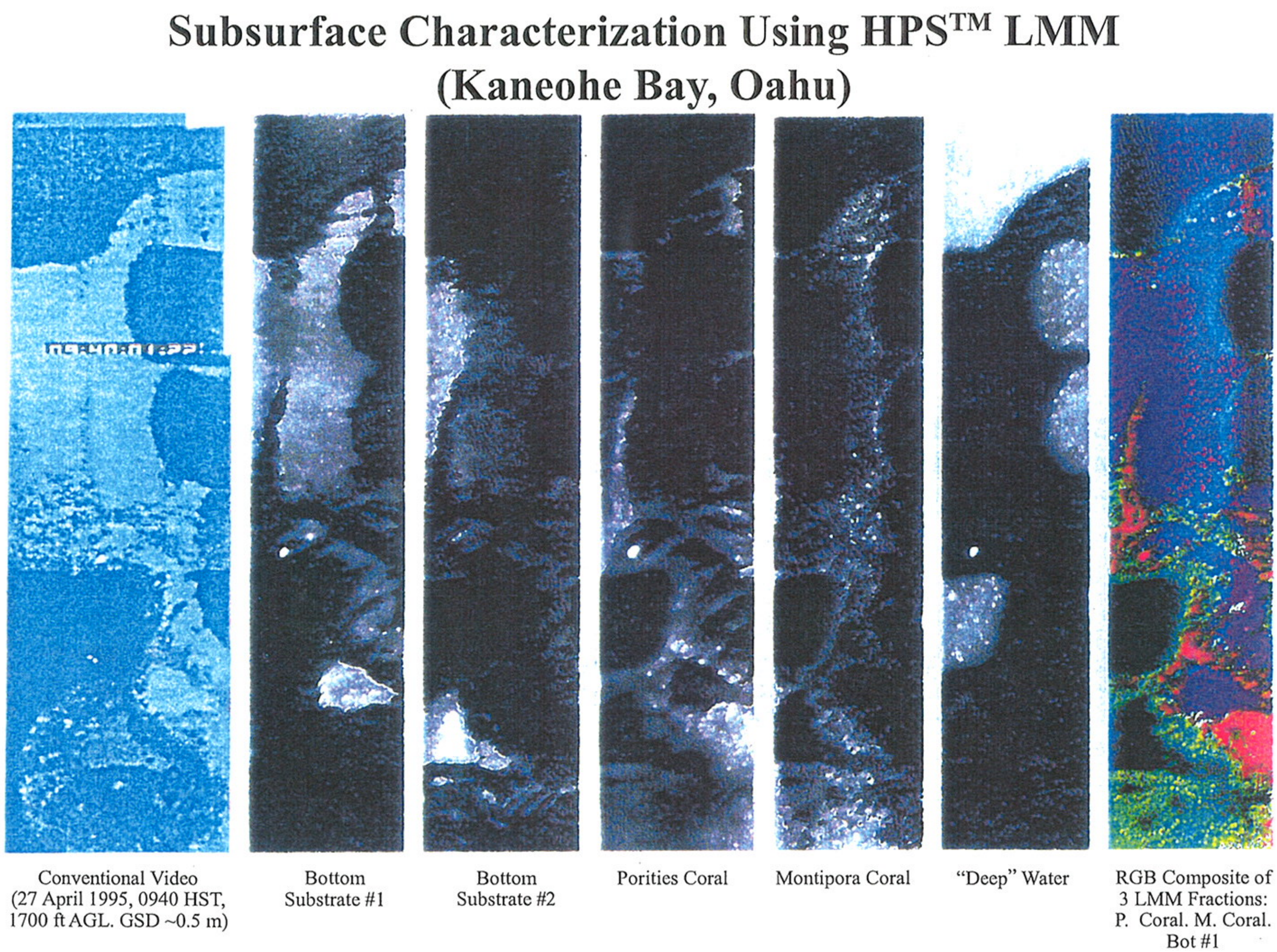

Fig. 13. Subsurface Characterization using SETS Hyperspectral Scanning.

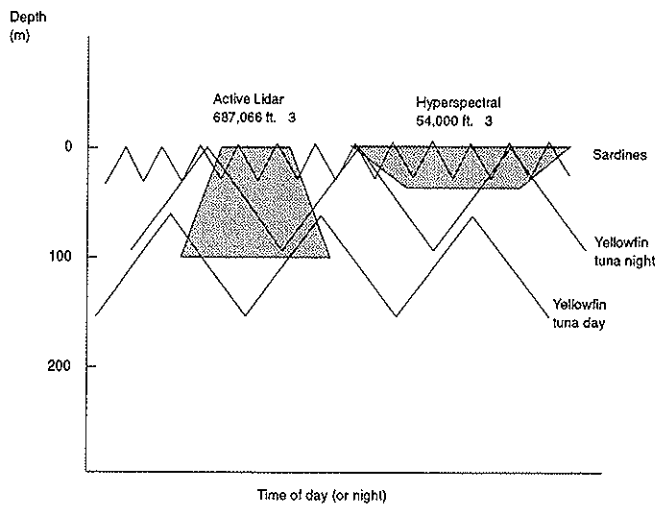

Fig. 14. Active lidar vs. Hyperspectral

•Resolution

Resolution for the lidar is determined by the pixel size of the ICCD and the beam diameter of the laser. For the hyperspectral system, in one dimension it is limited by pixel size of the detector and the optics controlling swath size to be collected, and in the other dimension it is limited by the speed of the electronics and the speed of the plane. In the cases presented here, both resolutions are easily acceptable for fish detection and identification.

•Power, Cooling, and Weight

Surprisingly, what the active lidar requires in a laser, is matched equally in power and weight in a computer by the hyperspectral system. With the commercial availability of embedded, fast, low-power (and low cost) PCs, both computer requirements could be reduced significantly.

Conclusions and General Recommendations

The results of the feasibility test show clearly that large pelagic fish can be detected and correctly identified by airborne lidar at ecologically meaningful depths in the water column. However the dispersed distribution of these fish and limited swath width of the instrument make it doubtful that these devices will be useful in the near future as survey devices. We recommend that

1. Specific fishery research problems be identified that can be addressed by these instruments; and
2. Hardware appropriate to the solution of such problems be developed by a team composed of biologists and engineers.

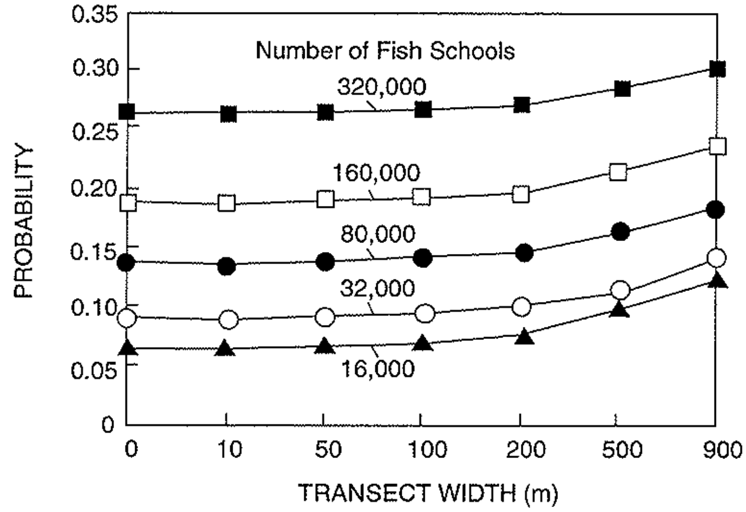

Fig. 14. Active lidar vs. Hyperspectral

Specific Recommendations

1. Assemble a ruggedized version for helicopter deployment. The system should integrate new state-of-the-art components, keeping an open frame architecture. Referring back to Fig. 1, the open framework would involve a modular assembly allowing for specified optical components to be installed in front of the ICCD. This would include the possible installation of an acousto-optic tunable filter (AOTF), to enable imaging of both fluorescence and Raman. Raman will give temperature information, and fluorescence will image chlorophyll and phyocerythrin.
2. Allow for installation of an imaging spectrometer and detector to replace the ICCD. This would allow for hyperspectral analysis of fluorescence signals to increase the detection and identification of fish. Combining hyperspectral and active lidar provides a powerful opportunity which to this point has not been exploited.
3. Utilize the services of an outside company to design and assemble the system.
4. The prototype should be made available for further research and development including possible AOTF and hyperspectral capabilities.
5. Research and development should be supervised by a fisheries specialist to ensure that requirements of target applications are met.

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