

Underwater Optical Imaging: Status and Prospects

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Introduction

As any backyard stargazer knows, one simply has to look up at the sky on a cloudless night to see light whose origin was quite a long time ago. Here, due to the fact that the mean scattering and absorption lengths are greater in size than the observable universe, one can record light from stars whose origin occurred around the time of the big bang. Unfortunately for oceanographers, the opacity of sea water to light far exceeds these intergalactic limits, making the job of collecting optical images in the ocean a difficult task.

Although recent advances in optical imaging technology have permitted researchers working in this area to accomplish projects which could only be dreamed of in years past, it makes sense to have a humble attitude and to realize that it is likely that the most sophisticated imaging systems in the sea are those of the animals, who depend upon their visual receptors in order to find prey, to mate, and to escape harm. Nevertheless, the recent decade has witnessed a large increase in our abilities to image objects in the sea. This is due to the current revolution in electronics and sensing technology coupled with advances in signal and image processing.

In this article, we intend to provide a brief history of underwater optical imaging and a brief summary of its relationship to other fields of ocean optics. However, our major task is to inform the reader about advances in underwater imaging that have occurred in the last decade. Without doubt, the bulk of our roots trace back to the work of Seibert Q. Duntley who was first at MIT and then at the Scripps Institution of Oceanography, where the Visibility Laboratory of the University of California San Diego was established. Duntley's classic article, "Light in the Sea" [Duntley, 1963], created a baseline of understanding which drew upon 20 years of studying light propagation for many uses including "photosynthesis, vision, and photography". Subsequent to that, there have been several books which have summarized a technical understanding of underwater imaging such as Merten's book entitled "In Water Photography" [1970] and a monograph edited by Ferris Smith [Smith, 1984]. An interesting conference which took place in 1970 resulted in the publication of several papers on optics of the sea, including the air water interface and the in water transmission and imaging of objects [Agard, 1973]. In this decade, several books by Russian authors have appeared which treat these problems either in the context of underwater vision theory [Dolin and Levin, 1991] or scattering through media [Zege, et al., 1991]. Recent years have also seen the development of many new types of imaging systems. The desire to image underwater objects is a goal shared (among others) by the Navy, pelagic ecologists, and geomorphologists.

Optical Propagation of Light in the Sea

Certainly the basic physics of the propagation of light in the sea influences the overall performance of underwater optical imaging systems as, for example, the transparency of the intergalactic medium to light creates opportunities for astronomers to view distant objects. In the sea, the inherent optical properties (IOPs) are the parameters which govern the propagation of light. So, for example, absorption and scattering must be taken into account in order to predict the performance of underwater imaging systems in various situations. Underwater imagers need accurate values for attenuation (for judging the ultimate distances at which underwater images can be formed) and a detailed knowledge of both forward scatter (which generally leads to a blur in the images) and backward scatter (which generally limits the contrast of underwater images by creating a “veiling glow”). Fortunately, recent advances in optical instrumentation for measuring these parameters (see companion article by Maffione) promise to increase our knowledge of these properties.

Since it is not always possible to perform measurements of the IOPs and, moreover, what is of interest in many oceanographic situations are the path averaged quantities, various researchers have examined issues related to underwater imaging on a more empirical basis. Since the major source of blurring in optical images is due to forward scatter, the relationship of the small angle volume scattering function (VSF), at angles close to directly forward, have been under investigation. Some of the earliest work in this area was accomplished by Mertens and Replogle [1977] who measured Point Spread Functions (PSFs) and established a relationship with the Beam Spread Function (BSF). More recently both experimental measurements of the Point Spread Function [McLean and Voss, 1991; Voss, 1991b], have provided validation of a small angle scattering theory and also experimental observations of PSFs with a parameterization of this function. Additional Monte Carlo simulations [Jaffe, 1995] have confirmed that there is an invertible relationship between the small angle scatter of the Volume Scattering Function (VSF) and the PSF for moderately deep optical depths (less than 5 total attenuation lengths).

Nevertheless, measurements at larger angles for the Volume Scattering Function have not been forthcoming. A single set of VSFs [Petzold, 1972] measured in San Diego Bay and environs in the 1960's have formed the basis for much examination and speculation about the imaging properties of water. The underwater imaging community eagerly awaits the development of modern Volume Scattering Meters and their deployment in a variety of different environments.

From the point of view of the environmental physicist, the ultimate property of underwater light field is radiance (neglecting the polarization properties as embodied by the Stokes vector). Therefore, no optical system built or envisioned needs to measure anything more. However, since radiance is both a time and space varying quantity its measurement can be complex. Sampling theorems related to both time and spatial measurements that would be necessary in order to provide unaliased views of the radiant field lead to some pessimistic conclusions. Since the spatial variability is ultimately related to the wavelength of light and temporal variability its bandwidth, spatial sampling may need to be quite high and the temporal changes in the light field can be quite rapid. Nevertheless, the latest generation of underwater

imaging systems take advantage of advances in light generation, sensing and data processing to obtain underwater images that were only dreamed about years ago.

Basics of underwater imaging

As in sonar systems, underwater optical imaging systems can be broadly classified into two areas: passive and active. Passive systems utilize light in order to image objects that have been illuminated by some source other than that associated with the imaging system. Examples are imaging of objects using sunlight or other sources of illumination such as bioluminescence. Passive imaging is especially attractive for covert operations such as fish seeking prey or the Navy inspecting objects without being detected. Active systems take advantage of a user generated source of light. A simple example is an underwater camera system which uses either strobe or continuous artificial illumination. These types of systems offer substantial benefits for underwater imaging in that the incident light can be collimated into very narrow beams, be monochromatic (lasers), with the option of very short duration (strobe, pulsed lasers). In this article, we will be mostly concerned with active systems. These systems typically allow imaging at greater ranges with higher contrast than passive systems which use sunlight. Moreover, with short pulses of lasers, they can be operated even in moderate levels of ambient light.

A basic classification for underwater imaging systems was formulated many years ago. Figure 1, adapted from [Jaffe, 1990] demonstrates the relationship between image range, camera light separation and the limiting factors in underwater image collection. If only short ranges are desired, a simple system with a controlled light beam and a good camera can yield excellent pictures as underwater photographers know. If longer ranges are desired, the separation of lights and cameras presents substantial advantages in that backscatter can be reduced

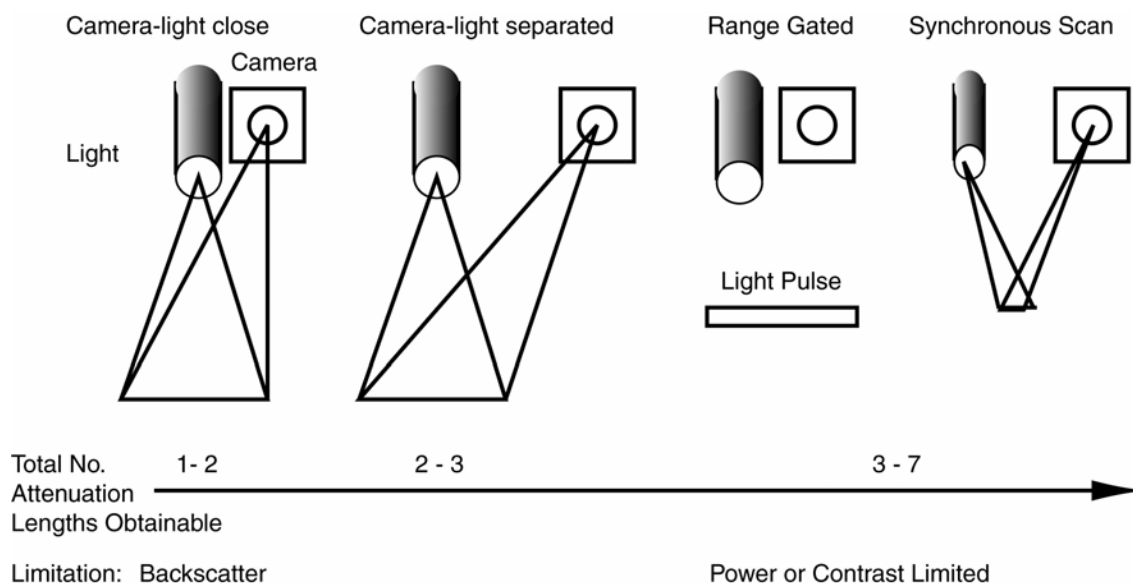


Figure 1: A Classification System for Underwater Image Collection Systems

substantially. This type of imaging was employed by the team that imaged the sunken luxury liner Titanic by using the two Russian MIR submarines. Further performance than this requires a bit more exotic technology. Two examples shown here are range gated imaging (where the backscatter is simply time-gated out) and synchronous scan imaging, which takes advantage of the concurrent scanning of a highly collimated source and a receiver with a narrow field of view. Although there seems to be continuing debate in the oceanographic community about which of these types of systems will yield better images (the authors here represent different views) it is certainly true that in order to obtain extended range imaging (better than 3 total attenuation lengths) from platforms which permit only limited camera light separation, some type of sophistication is needed beyond simply rearranging cameras and lights.

Current underwater imaging technology.

Imaging for Biological Observations

In this section we consider underwater imaging systems which have been used mostly for observing animals. Moreover, the systems described here are more sophisticated than the kind of system pictured in the left hand of Figure 1. A system which uses a sheet of light to illuminate its subject has substantial advantages for viewing a “slice” of a three dimensional object. Figure 2 illustrates the concept. The slice can be illuminated by either laser light or incoherent white light, such as a strobe. Palowitch and Jaffe [1993, 1995] demonstrated a lab based system for imaging the spatial distribution of phytoplankton which was subsequently used by Jaffe et al. [1998] and Franks [2001] in the ocean in both a monochromatic and multispectral mode. A further elaboration for using optical techniques to compute bubble size spectra was used by Stokes et al. [1999]. A new system by Benfield [2001] which uses a sheet of strobed white light for illumination promises to yield images of zooplankton over an image field of view of 12 centimeters with a resolution of 50 microns. The zooplankton imaging and visualization system (ZOOVIS) is a profiling instrument designed to collect quantitative images of mesozooplankton to depths of 250 m. The camera is aimed downward into a strobed light sheet that is 12 cm wide and 3 cm deep. By setting the depth of field to match or slightly exceed the depth of the light sheet, only targets that are in focus are illuminated.

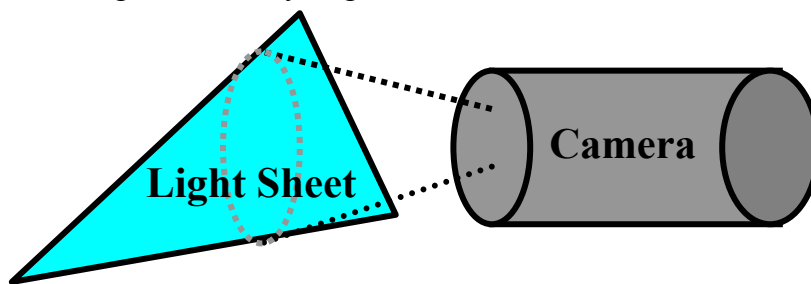


Figure 2: An example of a system that uses a light sheet for imaging

One system that has been used extensively in the field to characterize zooplankton distributions is the Video Plankton Recorder [Davis et al., 1994]. The system uses forward scattered light to image these animals which are nearly transparent. Several cameras image several volume sizes simultaneously in order to provide information on several size scales. An interesting system recently designed and built by Strickler and Hwang [2000] for obtaining

information about 3-dimensional trajectories of zooplankton (3D Zooplankton Observatory) uses Schlieren imaging with multiple cameras which obtain orthogonal projections of the animals in a 1 liter volume. The system permits viewing aquatic organisms ranging from phytoplankton to fish and promises to provide interesting information about zooplankton behavior in the lab. Although much has been learned about zooplankton using these systems, achieving the goal of using optical imaging systems to measure in-situ behavior of zooplankton, to the knowledge of one of the authors (J. Jaffe), has remained elusive.

Underwater optical holography has been an area which has seen development in the last decade. In the usual configuration, either “in-line” or “off-axis holography” geometric configurations have been used to record interference patterns on very high resolution film. Next, the interferograms are mounted on an optical bench where a facsimile of the configuration used to collect the images is assembled. A slice through the 3-dimensional volume is then viewed with a video camera or some similar device in order to obtain a set of slices through the 3-dimensional field of view. One of the first contributions to in-situ holography was due to Carder [1979]. One group in the United States which had been working on these problems for some time was under the supervision of A. J. Acosta of the California Institute of Technology. Several Ph. D. theses were authored in this area. Most recently, Katz has developed a holography system which uses an in line configuration in order to record coherent interference patterns which can be assembled into 3-dimensional volumes [Katz et al., 1999]. System resolution is on the order of 10’s of microns dependent upon orientation. Just this year, a group in Aberdeen has succeeded in deploying an underwater holographic imaging system which uses both in-line and off axis geometry in order to form a set of images [Watson et al., 2001]. The advantage of the off axis configuration is that it can work at higher densities of particles. Images from both of these systems have been very impressive. Understandably, holographic systems produce prodigious amounts of data, so that the automated analysis of such data is imperative.

Extended Range Imaging systems: Range Gated

As stated above, for extended range imaging (3 – 5 total attenuation lengths), the types of systems which are unavoidable involve the use of either range gating or synchronous scanning. In the simplest kind of range gated system, a short pulse of light is used to create a “slab” of illumination which is then reflected from the objects of interest. Activating the camera system at the precise time, determined from the range of interest then results in light which has traveled a fixed delay and is relatively free of backscatter information. As shown in Figure 1, these systems will ultimately succumb to a blurred image, via forward scattering, however, they are fully capable of providing good images at extended ranges.

A system which has been underdevelopment by Canadian Researchers [Fournier et al., 1993] uses a range gated approach coupled with image averaging to form range gated images. The LUCIE (Laser Underwater Camera Image Enhancer) system uses a laser which emits short pulses of light which are then reflected by the targets and imaged by an intensified CCD camera. The intensified camera and laser system are synchronized so that the camera is turned “on” after a specific delay in the round trip propagation of the light. Light, whose round trip travel time is commensurate with the timing of the laser generation and the image system being turned on is sensed and hence a relatively backscatter free image is recorded. A clever aspect of the LUCIE system is that very high repetition rate 2,000 pulses per second is used. This allows on chip averaging of the collected light via the collection of repeated images and compensates for the

poor signal-to-noise of previous systems which used only one image. The system provides video rate information about objects and is diver safe. A newer prototype, under development will use a more powerful laser, increase the field of view and therefore provide images with higher clarity in murkier conditions.

Range gated systems can also be used through the air-sea interface. The great advantage of air deployed systems is that they have the capability to couple the survey speed of helicopters or small planes, with the imaging speed of light. This provides a potentially very rapid way for the survey of underwater objects, however, it requires that the system image through the sea. Since this both a temporally and spatially varying phenomena, whose statistics are perhaps only known, it is a difficult problem. The Magic Lantern System by Kaman Aerospace (Tucson, AZ) was used successfully in the gulf war to detect the presence of subsurface suspended mines [Ulrich et al.]. Another set of systems have been advocated for fish surveys of epipelagic fish. [Churnside et al. 1997]. Variations of these systems range from simple scanning hardware with gated PMTs (Photon Multiplier Tubes) to systems which are quite similar to the range gated system described above. Results, to date, present fuzzy images which might be adapted for estimating the sizes and abundances of fish or other objects, however imaging the details of underwater objects is a difficult problem (McLean and Freeman, 1996).

Extended Range Imaging: Range Gates: Streak Tube Imaging Lidar

A recent advance in time resolved imaging is a system which utilizes a fan beam of pulsed laser light coupled with fast receive hardware which permits time resolution of the reflected illumination. Developed by Arete Associates, the Streak Tube Imaging Lidar: (STIL)¹, has recently demonstrated high resolution 3-D imaging for electro-optic identification (EOID) of underwater objects. As a lidar system, STIL measures the time of flight. However, a new feature is its capability to measure the amplitude of the backscattered signal as well. This data can be processed to form both a contrast image and a range image, in order to provide a full 3-D representation of the underwater scene. For EOID, design goals are 1.25 cm lateral resolution, and 2.5 cm range resolution.

STIL is an active imaging system using a pulsed laser transmitter and a streak tube receiver to time resolve the backscattered light. The laser beam is spread in one dimension using a cylindrical lens to form a fan beam (Figure 3). The backscattered light is imaged by a conventional lens onto a slit in front of the streak tube photocathode, and is time (range) resolved by electrostatic sweep within the streak tube, generating a 2-D range-azimuth image on each laser pulse (Figure 4). By orienting the fan beam perpendicular to the vehicle track, the cross-track dimension is sampled by adjusting the pulse repetition frequency (PRF) of the laser to the forward speed of the vehicle, thus sweeping out the three-dimensional ocean volume in a pushbroom fashion. This scannerless implementation provides full coverage of the volume without moving parts.

¹ Patent 5,467,122

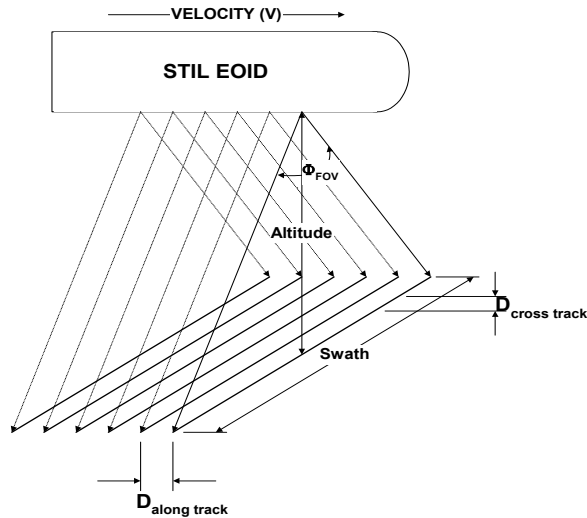


Figure 3. STIL concept of operations. Fixed optics project a fan beam (crosstrack) on each laser pulse. Along-track sampling is determined by the speed of the platform and system PRF.

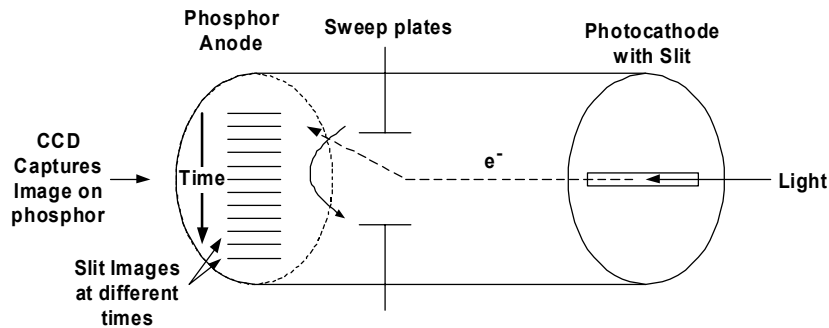


Figure 4. Streak tube operation. Photoelectrons from the slit photocathode are accelerated by an axial electrostatic potential, and steered through parallel plate electrodes. The photoelectrons are then converted back to photons at the phosphor anode. The resulting range-azimuth image is read out digitally using conventional CCD technology.

Figure 5 is a single shot range-azimuth image illustrating the exponential decay of the water backscatter and the return from the bottom, and illustrates how the water backscatter is temporally separated from the bottom return, providing outstanding backscatter rejection. This precise temporal sampling also makes the sensor immune to ambient sunlight. The bottom return includes both time of flight information which provides a quantitative measure of the height of the object above the bottom (a truncated cone in this case), and the radiometric level that is proportional to the reflectivity of the bottom object. Each laser shot thus provides range to and contrast of the bottom, for each cross-track pixel. By aligning this pixel information along-track, both range and contrast images of the bottom scene are obtained (Figure 6).

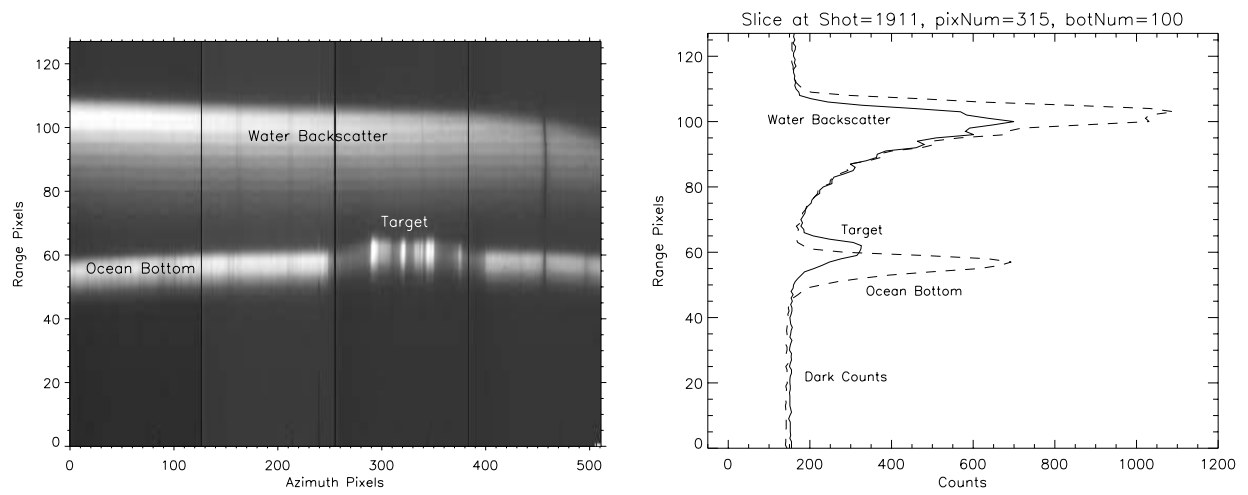
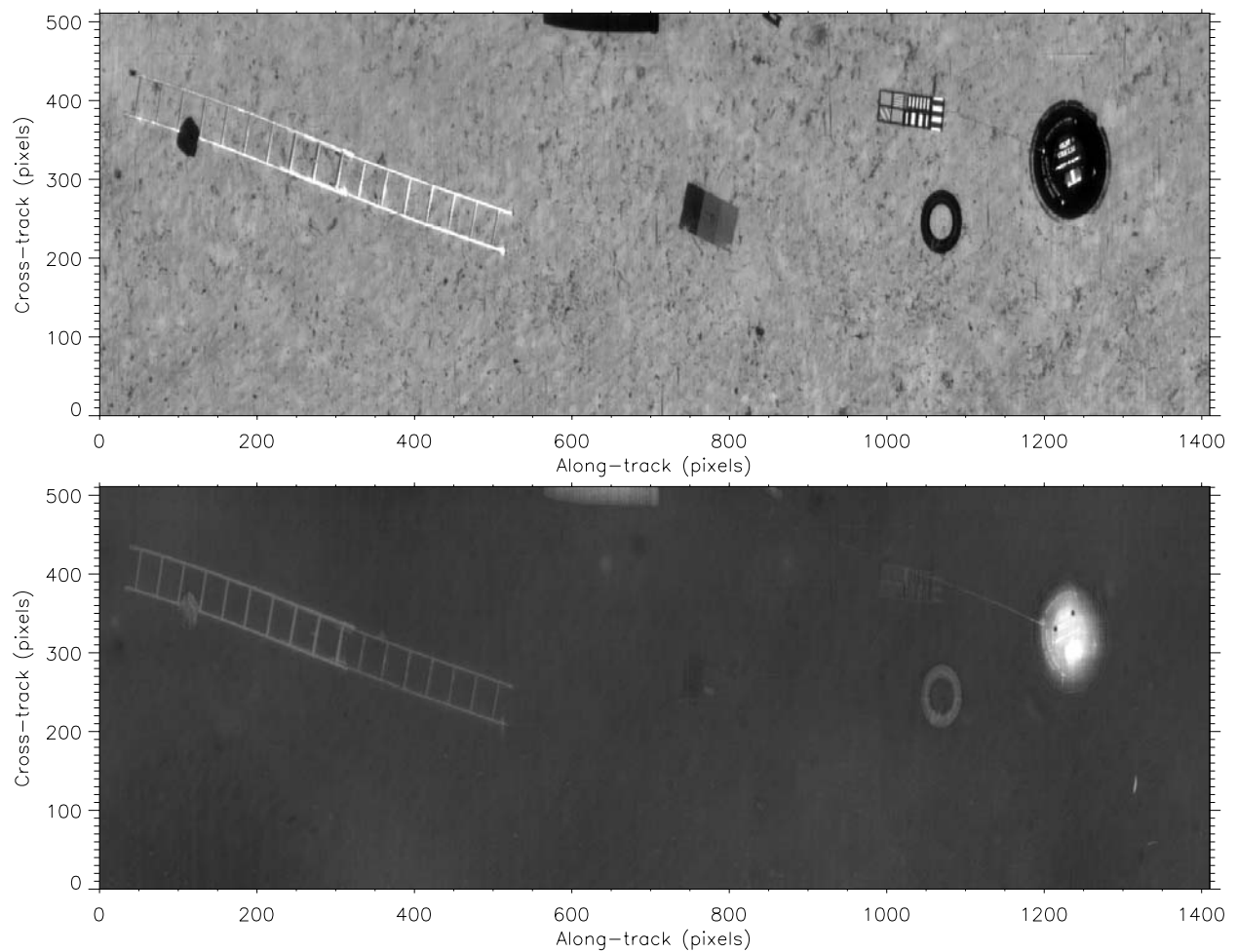


Figure 5. Single shot range-azimuth image (left), and range cut, showing exponential decay of water backscatter, range information from time of flight, and contrast information from amplitude of bottom return. The resulting multi-shot image scene is shown in Figure 4.



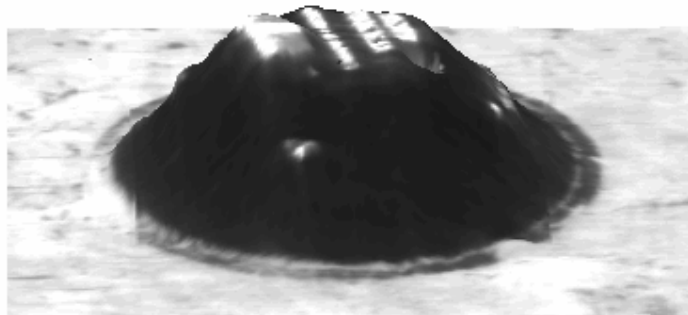


Figure 6. Contrast (top) and range (middle) images at 24' depth, including ladder, contrast panel, resolution panel, tire, and truncated cone (30" diameter by 18" high). Note the small fish at lower right in the range image. The data can be combined to generate a perspective view of the object (bottom).

Under sponsorship by the Office of Naval research², STIL technology has matured from a laboratory proof of concept to an integrated, fieldable capability. The first generation system was developed in 1995 using a commercially available streak tube system to demonstrate 3-D imaging capability in laboratory and controlled field test experiments. The second generation system was developed in 1998 to address the packaging and ruggedization requirements for a underwater deployable configuration. The third generation system (Figure 7), represents a compact, deployable configuration suitable for deep ocean surveillance.

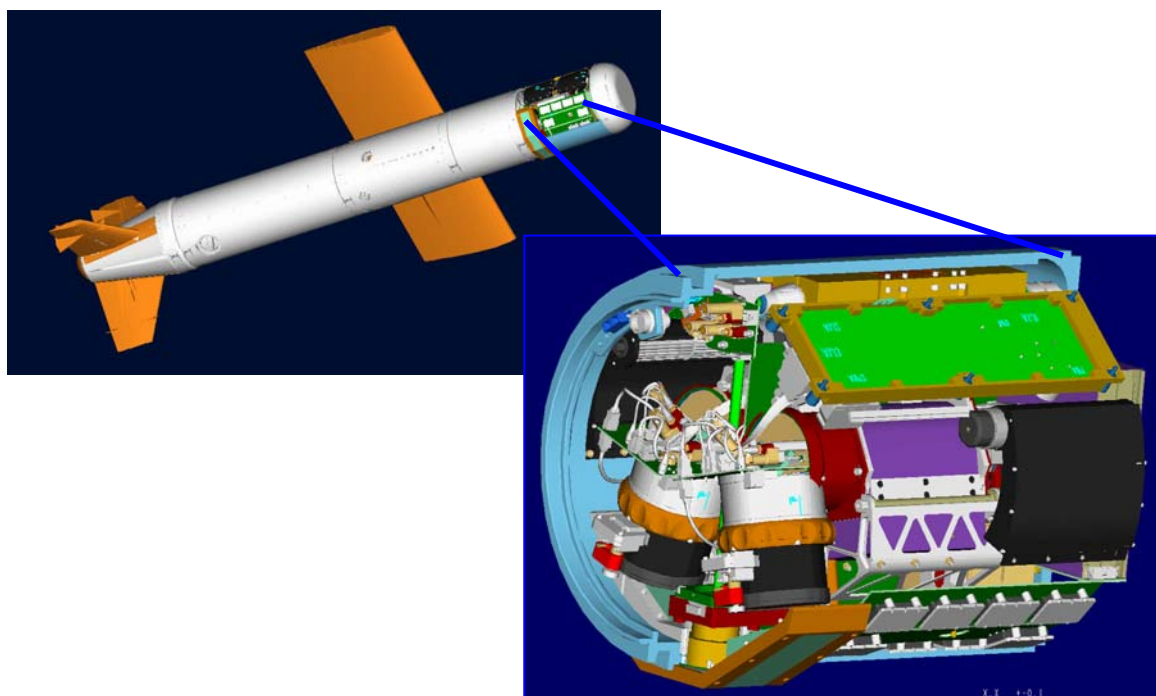


Figure 7. EOIDS sensor integrated into a deployable tow body. Body is approximately 15” in diameter by 10’ long. The EOIDS sensor is in the nose of the vehicle, and approximately 20” long.

In collaboration with the Navy’s Coastal System Station in Panama City, Florida, this integrated system was tested during the summer of 2000 in the Gulf of Mexico. The vehicle was deployed from both a surface ship as well as helicopter, at speeds up to 25 knots. Under the relatively clear water conditions encountered during this experiment, image quality was extremely good (Figure 6), and bottom objects could be clearly identified. Performance under turbid water conditions was significantly degraded, as expected. For quantitative evaluation of performance over a wide variety of water types, additional testing is planned for summer 2001 in the Gulf of Mexico, and in summer 2002 off of the Florida Keys.

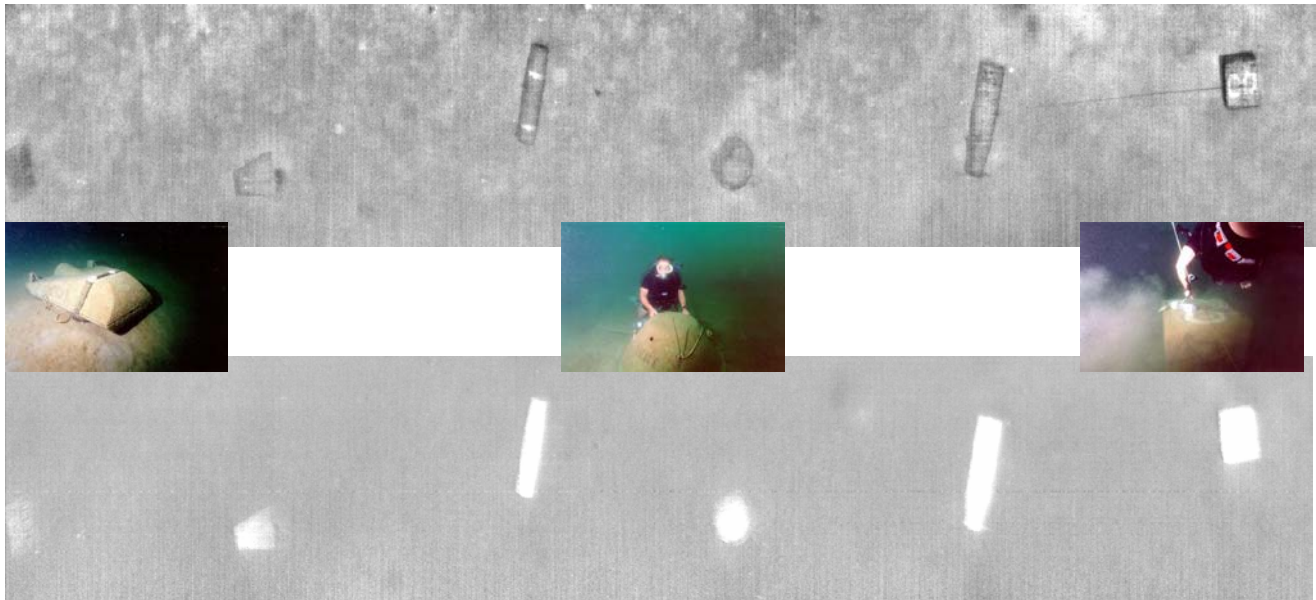


Figure 8. Contrast (top) and range (bottom) images of Gulf of Mexico target field. Insets are photographs of objects. Note the number “8” painted on the object at right.

Extended Range Imaging Systems: Scanned: Laser Line Scan

In the case of synchronous scanning, an approach called the Laser Line Scan (LLS) system has been under development for a little more than a decade, primarily by Brian Coles of Raytheon [Leathem and Coles, 1993; Coles, 1997]. The system consists of a highly collimated CW laser beam that is passed through a rotating mirror so that it may scan the sea floor in a direction perpendicular to platform motion. A sensitive set of receive optics is “synchronously scanned” so that only light from a small area of the sea floor which has mostly not been scattered in the intervening water is imaged. As a recent enhancement to this system, a color version that permits up to four different wavelengths was developed. Figure 9a shows a simplified

schematic diagram of the experimental four-receiver Laser Line Scan sensor. Each receiver consists of a rotating input optical assembly, a controllable aperture assembly, a photo-multiplier tube, a preamplifier and signal conditioning electronics, and an analog-to-digital converter. The four rotating input optical assemblies and a rotating output optical assembly are mounted on a drive shaft to ensure mechanical synchronization of the laser spot and the receiver spots across the sea floor. The input/output optical assemblies employ four-faceted mirrors, yielding four 90-degree scan lines per rotation of the drive shaft. Scan line (cross track) imagery is formed from the center 70-degree portion of each scan line by digitizing the electrical output from each receiver to 12 bits at a user selectable (512, 1024, 2048, or 4096) number of pixels per scan line. Two-dimensional imagery is formed by platform motion, ensuring that successive scan lines are displaced from each other.

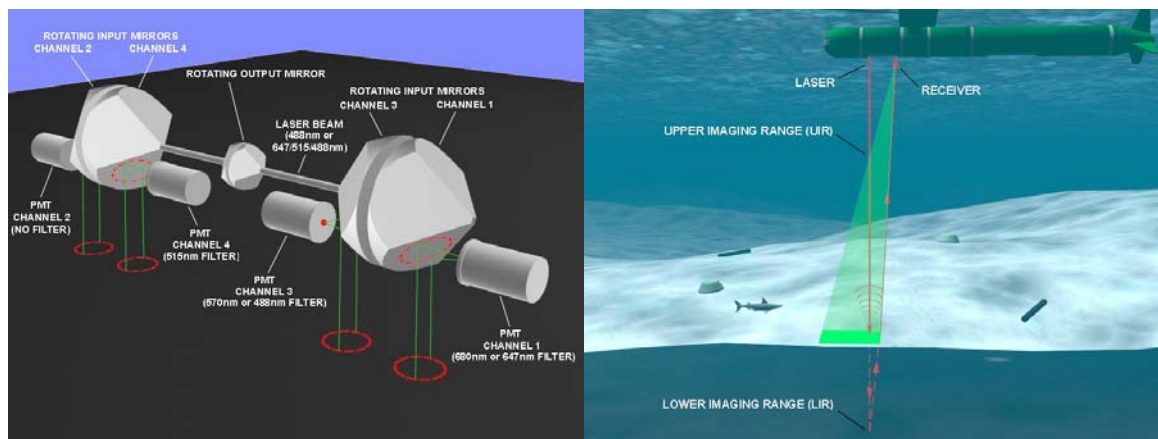


Figure 9. (a) A simplified schematic diagram of the four-receiver LLS sensor used for FILLS or RGB-color imagery. (b) For each receiver, the upper imaging range (UIR) is the near range where the field of view of the scanner intersects the laser beam, while the lower imaging range (LIR) is the far range where the extrapolated field of view of the scanner intersects the extrapolated laser beam.

The pixel size produced by this sensor depends upon sensor altitude, tow speed, scan rate, and the number of pixels per scan line. The along track pixel size in centimeters is $771 * \text{Speed(knots)} / \text{RPM}$, where RPM is the number of revolutions per minute of the scanner drive shaft. The scan speed is user controllable with an upper limit of 4000 RPMs. The cross track pixel size in centimeters is $122 * \text{Altitude(m)} / \text{Npixel}$, where Npixel (512, 1024, 2048, or 4096) is the number of pixels per 70 degree scan line. As an example, 1 centimeter along track and cross track pixel sizes are achieved at an altitude of 8.5 m and a tow speed of 5.2 knots when the scanner is operated at 4000 RPMs and 1024 pixels per scan line.

This sensor can be configured in several ways to acquire different types of data. In the Fluorescence Imaging Laser Line Scan (FILLS) configuration, the laser is an Argon Ion laser with its output tuned to 488 nm, and the four receivers are fitted with interference filters centered at (for example) 680 nm, 488 nm, 515 nm, and 570 nm respectively. In this configuration, channel 2 images with elastically scattered light, while channels 1, 3, and 4 image with red, green, and yellow light, respectively. The source of this red, green, and yellow light is predominantly natural fluorescence stimulated by the 488 nm laser light. (However, because of

their spectral proximity, there is some “leakage” of the elastically scattered 488nm light into the green channel image.) In a second configuration, the laser can be an Argon/Krypton mixed gas laser, which produces simultaneous outputs at 647nm (red), 515nm (green), and 488nm (blue). When three of the receivers are fitted with matching filters, the data required to produce RGB color imagery can be obtained. In this configuration no filter is installed in the remaining channel.

LLS sensors reduce the detrimental effects of backscatter and blur/glow/forward scatter by producing imagery from a very small laser spot and small, synchronously scanning, receiver spots [Strand, 1997]. As illustrated in figure 9b, the receiver spots on the sea floor are roughly rectangular shaped. The cross track width of receiver spot is typically 10 milliradians or less. The user controllable depth of field of the sensor determines the along-track length of the receiver spot. The depth of field is controlled by the upper imaging range (UIR) and lower imaging range (LIR) of the sensor, which are set to bracket the sensor altitude. Physically, the UIR and LIR of each receiver are controlled through an aperture assembly in front of each PMT. For this sensor, the minimum UIR is about 15 feet. Practical maximum upper and lower imaging ranges are set by water visibility conditions. We next present examples of imagery that have been taken with the system under a variety of environmental conditions.

Monitor

In October 1996, the 4-channel LLS sensor in its RGB configuration was used to image the famed Civil War ironclad USS Monitor. The Monitor presents significant imaging challenges, but serves to illustrate several of the characteristics of LLS sensors. As the sketches (adapted from sketches provided by the Monitor National Marine Sanctuary) in figure 10 show, the Monitor is a large inverted structure with large portions at significantly different heights above the seabed. First, the inverted turret rises 6 feet above the seabed. The armor belt, resting on top of the turret, is 5' high and 7' wide. Portions of the lower hull are up to 18 feet above the seabed, while other portions have collapsed down toward the seabed. The profile of the Monitor presented significant depth of field challenges. High currents, poor visibility, and poor weather presented other challenges. Weather conditions restricted imaging to 2 missions of approximately one hour each.

Figure 11 shows a mosaic constructed from LLS imagery acquired during the two missions. The turret, port armor belt (the starboard armor belt has disintegrated), skeg, propeller and propeller shaft, and intact and collapsed portions of the lower hull are clearly visible in the mosaic. The imagery presented here is obtained from the unfiltered receiver channel. The substantial depth of field capabilities of LLS sensors are illustrated in Figure 12a, which shows a portion of the turret, rubble in the turret, the armor belt, and a collapsed portion of the lower hull. This imagery demonstrates the one of the benefits of the high intra-scene dynamic range provided by the 12 bit digitization. Special processing techniques have been developed in order to better display or print this 12-bit imagery on media that, at best, reproduces 8 bit imagery [Nevis 1998, 1999, Nevis and Strand 2000]. Figure 12b is a zoomed sub-image of figure 12a, showing detail, including a coiled cable, in the lower hull rubble.

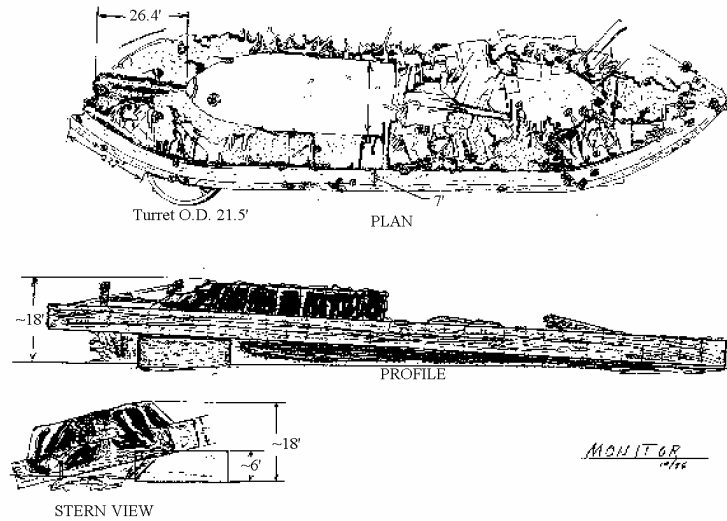
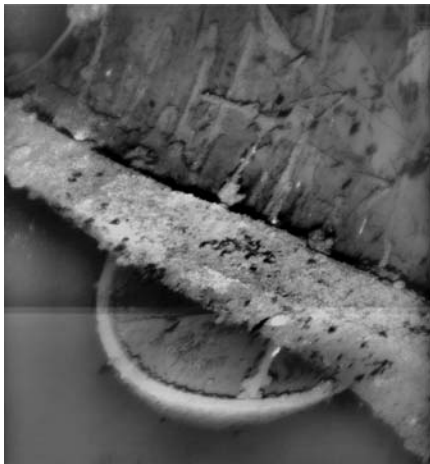


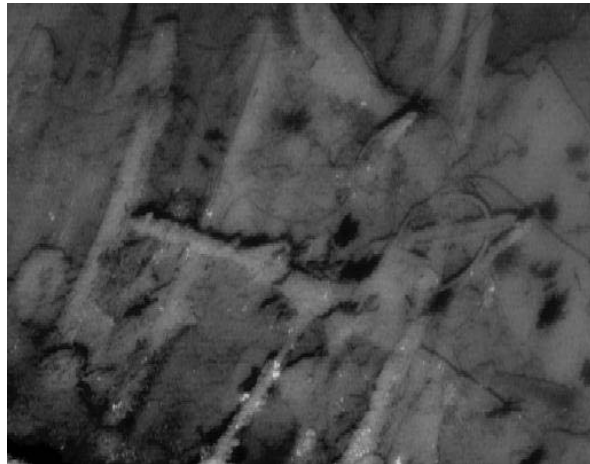
Figure 10: A Schematic of the hull of the Monitor as it rests on the sea floor.



Figure 11: A mosaic of the remains of the Monitor taken from LLS imagery.



(a)



(b)

Figure 12a and 12b. A portion of the turret, armor belt, and the collapsed lower hull (a) and a close up (b) showing coiled cables in the collapsed lower hull.

Extended Range Imaging Systems: Scanned: FILLs imagery

The fluorescence characteristics of corals present a remarkable environment for deployment of the 4-channel LLS sensor in its FILLs configuration [Strand et al., 1996]. Figure 13 a-d shows FILLs imagery for the elastic scatter channel and each of the fluorescence channels. Figure 6e shows a pseudo-color image constructed from the individual fluorescence channel images by mapping red fluorescence to red, green fluorescence to green, and yellow fluorescence to blue (the remaining primary color.) Certain hard coral species give relatively strong green and/or yellow fluorescence signals. Soft corals typically give relatively strong red fluorescence signals. In addition, the carbonate sediment gives a lower level of fluorescence in all three fluorescence channels. The high gain capabilities of the PMTs are required in order to produce good FILLs imagery, particularly in the red channel. First, the fluorescence signal levels are markedly lower than the elastic scatter signal levels. Second, the large absorption coefficient of water in red leads to strong attenuation of the already weak fluorescence signal. For this reason, the red channel is almost always run at maximum gain, and better red fluorescence imagery is obtained at lower scanner RPMs.

Figure 14 shows another environment that yields remarkable FILLs imagery. It shows the elastic scatter and fluorescence pseudocolor images of stromatolites near Lee Stocking Island in the Bahamas. It is evident that, when stimulated by the 488nm laser light, the stromatolites produce significant red fluorescence signals. This imagery was acquired at a 5 knots tow speed and a scanner speed of 2000 RPMs. The tow body altitude was 4.5 meters, and its depth was 1 meter.

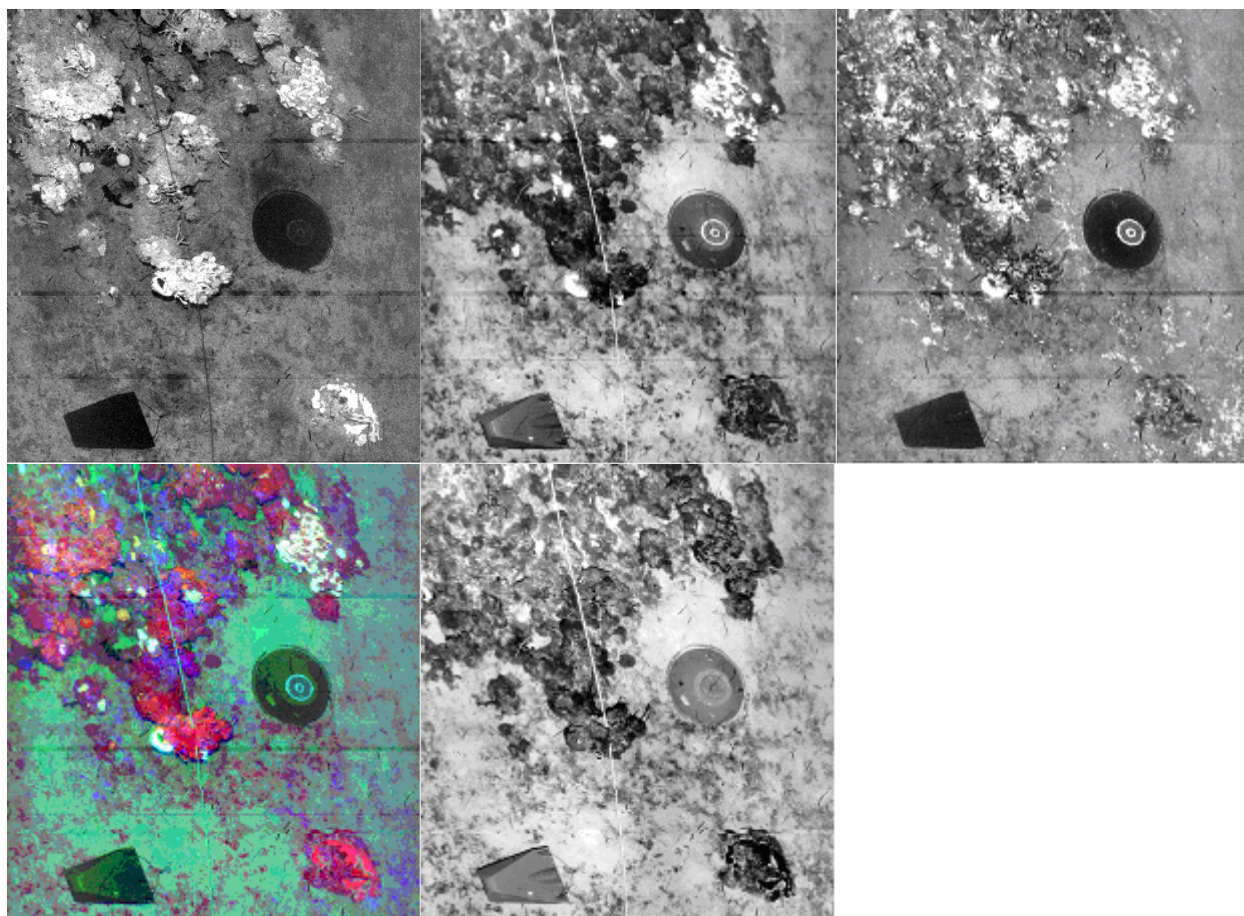


Figure 13. The top row (a-c) shows images from the red, green, and yellow channels of the FILLS sensor. These are formed primarily from fluorescence stimulated by the 488nm laser, although there is some leakage of reflected 488nm light into the green channel. The bottom row compares the pseudocolor fluorescence image (d) with the corresponding image formed from reflected 488nm laser light (e).

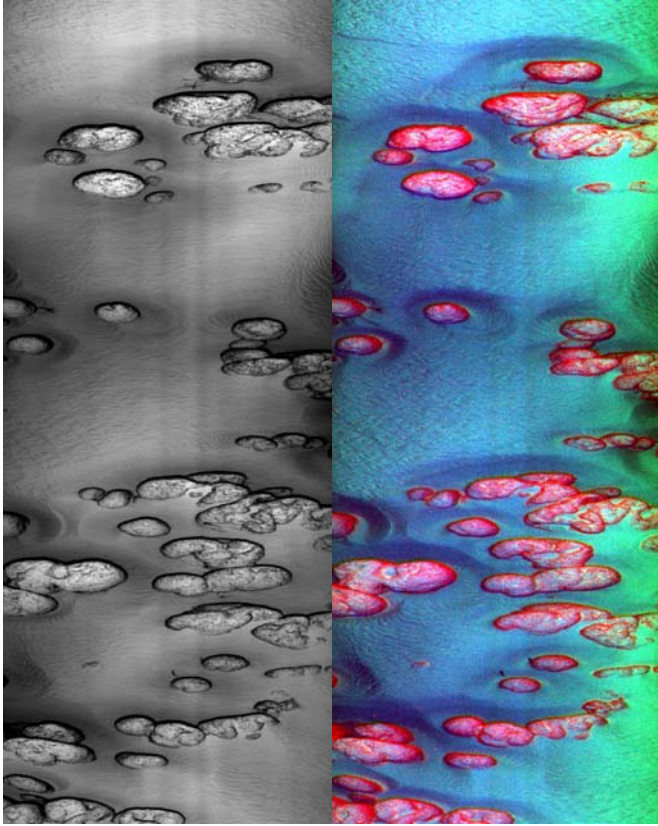


Figure 14. FILLS images of stromatolites in the vicinity of Lee Stocking Island. The left image is formed from elastically scattered light at 488, the right image is a pseudocolor image created primarily from fluoresced light.

Extended Range Imaging Systems: Scanned: 3D Sea Scan

The 3D Sea Scan, a very recently built system, has the capability like STIL of obtaining 3-dimensional images. However, like LLS it uses a scanning. In this case, instead of having a sensitive PMT for light detection, a one dimensional CCD array is used. Figure 15 shows a picture of the system. As in PHILLS, the 3D Sea Scan system scans a collimated laser beam from side to side. The volume which is illuminated by this system can be considered to be a plane or sheet. Concurrently, a one dimensional CCD array images light whose origin is in the same plane. This one dimensional array creates a record of a line through the radiant profile that has been created by the sheet illumination. In simple situations, where the water is clear, the bottom reflection of the light can be easily identified and the system can use both the intensity of the reflected light as well as it's position to judge bottom reflectance and also range. In more turbid conditions, more sophisticated algorithms can be used to measure both the volume scatter in the water column as well as the reflection of light from the sea floor. Object range can be inferred via the use of a scheme which, at its heart is an application of the principal of triangulation. For moderate altitudes: 3 m – 5 m, the system can achieve excellent range resolution: 2 mm – 5 mm. The system uses source-receiver separation for both good image

quality and also the triangulation scheme, which here are mutually desirable. Papers detailing the basic system configuration with preliminary results [Moore et al., 2000] a system calibration for achieving submillimeter accuracy [Moore, 2001], and recent results with the system in measuring a time evolving bottom profile [Moore and Jaffe, 2001] have been documented.



Figure 15. The 3DSEAS system being launched.

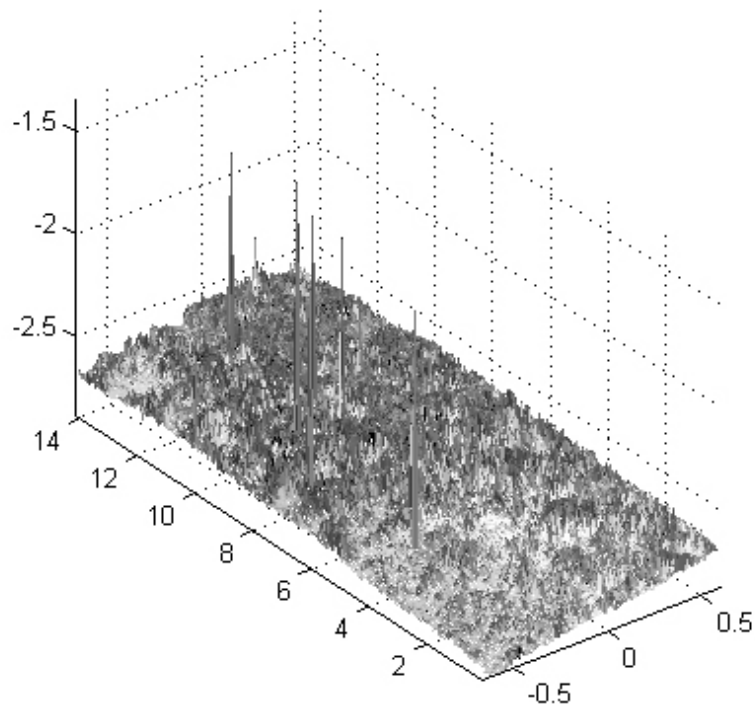


Figure 16. A 3-dimensional rendering of a field of Turtle grass from Lee Stocking Island
All scales are in meters.

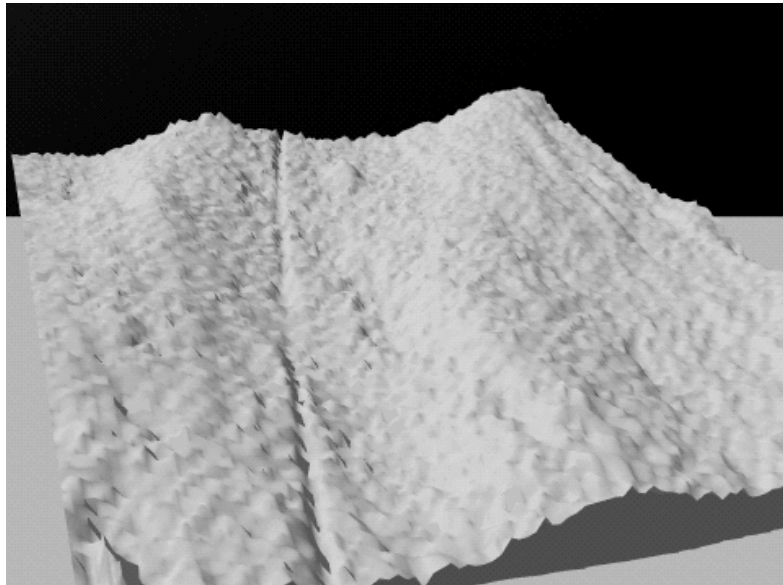


Figure 17. A 1.4 x .85 meter field of view taken with the 3D Sea Scan system. The range and reflectance data was input into the Bryce system of computer programs for visualization.

Figure 16 shows the result of processing data that was recorded when the system was towed over a field of turtle grass. The vertical axis shows the depth of the objects below the system. The other two axes are in meters, showing the extent of the recorded image. Note that the sea floor in this area is white sand and that the grass is seen as the darker objects protruding out of the sea floor. Several large spikes can also be seen in the Figure. These are likely due to fish which were suspended over the sea floor, however only reflected light was collected from them in one scan. As a final figure, Figure 17 shows a 3-dimensional image which was recorded as part of an ONR field program to monitor bottom scatter of acoustics and the temporal and spatial characteristics of the sea floor which lead to the observed acoustical effects. The image shows an area of the bottom which measures approximately 1.4 m x .85 m. For the purpose of acquiring this image, an underwater frame was developed which facilitated the precise positioning of the system over the sea floor. The system was suspended from a frame and translated precisely over this 1.2 meter track. The recorded data were analyzed to provide an estimate for both the reflectivity of the sea floor as well as its topography. The images of these two parameters were then input into the Bryce [Metacreations, CA] system of computer rendering programs in order to provide a shaded display of the data which used the range image as an altitude map and the reflectance image as a map of surface reflectance. Interactive manipulation of this data base provides interesting views of the data which reveals many features of the bottom. The image shows several underwater sand waves with an aggregation of larger stones in the depressions and finer sand at the crests. Time evolving records of the bottom were also taken along a one dimensional transect by holding the imaging system fixed. These records have provided an interesting view of the flattening of the sea floor over a 9 day period with the subsequent onset of the regeneration of the sand waves at the beginning of a storm [Moore and Jaffe, 2001].

Future prospects for underwater imaging:

Although it is probably true that the most sophisticated types of passive underwater imaging systems in the sea are those of animals, it is reasonable to say that we have only limited knowledge of how animals see underwater. Considering underwater vision systems from the physical optics, photoreceptors and neurophysiological avenues of inquiry will yield new insights into optical system design, the biochemistry and biophysics of photoreceptors and the information processing of underwater images.

An additional area that has seen only limited application in underwater imaging has been the use of confocal techniques [Wilson and Sheppard, 1984]. For many years, confocal microscopy has been one of the most valued techniques for obtaining three dimensional image of microscopic sizes. The technique takes advantage of a pinhole aperture which is coupled with a point source. Both are “confocal” that is, in the same focal plane of a lens which is used both for illumination and also collection of images. There is a slight increase in resolution when using this method, however for the underwater oceanographer, the vast advantage is the elimination of scattered light that is not confocal to either the laser source or the pinhole aperture.

Finally, the very latest generation of optical systems has started to yield multidimensional PMT arrays which start to make the goal of achieving time varying images with adequate spatial and temporal resolution a possibility for future generation systems.

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