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 the Massachusetts Institute of Technology (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" (Mertens, 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 imaging through scattering 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 pelagic and benthic ecologists, geomorphologists and marine resources management personnel.

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 that 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. For purposes of system modeling and simulation, accurate data are needed for attenuation, in order to estimate imaging distances, forward scatter, which leads to image blur, and backward light 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 article this issue 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 nature of the near-forward Volume Scattering Function (VSF) has been the subject of investigations during the past quarter of a century. Some of the earliest work in this area was accomplished by Mertens and Replogle (1977) who measured how light within the ocean propagated from a point source, expressed as the Point Spread Function (PSF), compared with how a beam of light propagated across the same distance, expressed as a Beam Stread Function (BSF). More recently experimental measurements of the PSF (McLean and Voss, 1991; Voss, 1991), have provided validation of a small angle scattering theory and also experimental observations of PSFs with a parameterization. Additional Monte Carlo simulations (Jaffe, 1995) have confirmed that there is an invertible relationship between the small angle scatter of the VSF and the PSF for optical depths less than 5 total attenuation lengths. Unlike near-forward angles, instrumentation to routinely measure the details of the VSF at larger angles has yet to be developed. A single set of VSFs (Petzold, 1972) measured in San Diego Bay and environs in the 1960s 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 VSF 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 spatial and temporal 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.

Principles 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 that 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 by Duntley and coworkers (1960s) and is summarized in Figure 1, adapted from Jaffe (1990). 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 greatly. This approach was employed by the team that imaged the sunken luxury liner Titanic by using the two Russian MIR submarines.

Better 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 three 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 that have been used mostly for observing animals. Moreover, the systems described here are more sophisticated than the kind of system pictured in the left side of Figure 1. A system that uses a sheet of light to illuminate its subject has substantial advantages for

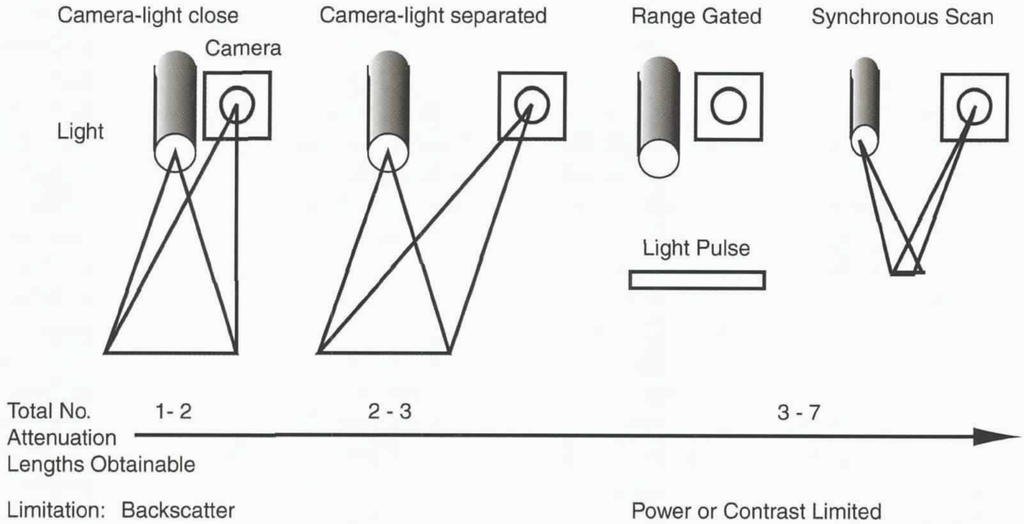


Figure 1. A classification system for underwater imaging systems. The trade-offs between camera light separation, more exotic imaging systems (range gated and synchronous scan) and the obtainable viewing distances are shown.

viewing a "slice" of a three-dimensional object. 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 that was subsequently used by Jaffe et al. (1998) and Franks and Jaffe (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 and Deane (1999). A new system by Benfield et al. (2001) that 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 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.

One system that has been used extensively in the field to characterize zooplankton distributions is the Video Plankton Recorder (Davis et al., 1992). The system uses forward scattered light to image these animals that 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 in conjunction with multiple cameras in order to 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 has remained elusive.

Underwater optical holography has been an area that 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 that 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 that can be assembled into 3-dimensional volumes (Katz et al., 1999). System resolution is on the order of 10s of microns dependent upon orientation. Just this year, a group in Aberdeen, Scotland has succeeded in deploying an underwater holographic imaging system that 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.

Range Gated Imaging Systems

As stated above, for extended range imaging (3–5 total attenuation lengths), the types of systems that are necessary 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, results in light that has traveled a fixed delay and is relatively free of backscatter information. While image distances for these systems are ultimately limited by near-forward light scatter and the resulting image blur, they are fully capable of providing good images at extended ranges.

A system which has been under development 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 that emits short pulses of light that are 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. Hence, an image that is relatively free of backscatter is recorded. A clever aspect of the LUCIE system is that it uses a very high laser repetition rate of 2,000 pulses per second. 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 that 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 surface. Since this is both a temporally and spatially varying phenomenon, the statistics of which is perhaps the only information available, it is a difficult problem. Regardless, the Magic Lantern System by Kaman Aerospace was used successfully in the Gulf war to detect the presence of subsurface suspended mines (Ulrich et al., 1997). Other systems have been advocated for surveys of epipelagic fish. (Churnside et al., 1997). Variations of these systems range from simple scanning hardware with gated PhotoMultiplier Tubes (PMTs) to systems that 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).

A recent advance in time resolved imaging is a system that utilizes a fan beam of pulsed laser light coupled with fast receive hardware that 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. These 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 with spatial resolution approaching 1.25 to 2.5 cm.

STIL is an active imaging system that uses a pulsed

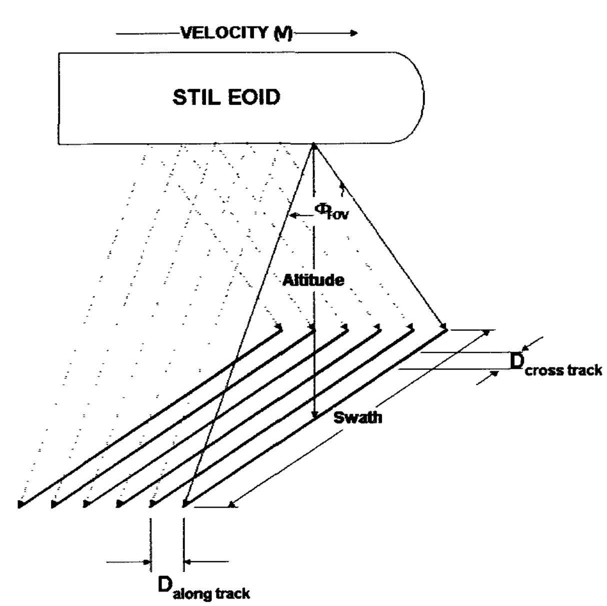


Figure 2. STIL concept of operations. Fixed optics project a fan beam (crosstrack) on each laser pulse. Along-track sampling is determined by the speed of the platform and system PRF.

[1] Patent 5,467,122.

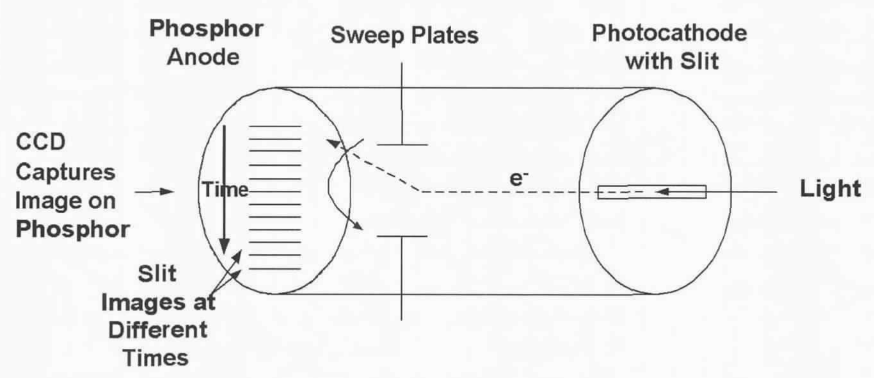


Figure 3. Streak tube operation. Photoelectrons from the slit photocathode are accelerated by an axial electrostatic potential, and steered through parallel plate electrodes. The photoelectrons are then converted back to photons at the phosphor anode. The resulting range-azimuth image is read out digitally using conventional CCD technology.

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 2). 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 3). By orienting the fan beam perpendicular to the vehicle track, the cross-track dimension is sampled by adjusting the pulse repetition frequency 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.

Since the backscattered light received by the STIL is highly resolved in time, much of the water column backscatter is temporally separated from the signal representing the ocean floor (Figure 4). This precise temporal sampling also makes the sensor less sensitive to the effects of ambient sunlight. The bottom return includes both time of flight information providing a quantitative measure of the height of the object above the bottom 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 5).

Synchronous Scanning

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 reflected from a rotating mirror and directed so that it scans the sea floor in a direction perpendicular to platform motion. A sensitive set of receive optics with a narrow field of view 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 6a). Each receiver consists of a rotating input optical assembly, a controllable aperture assembly, a photo-multi-

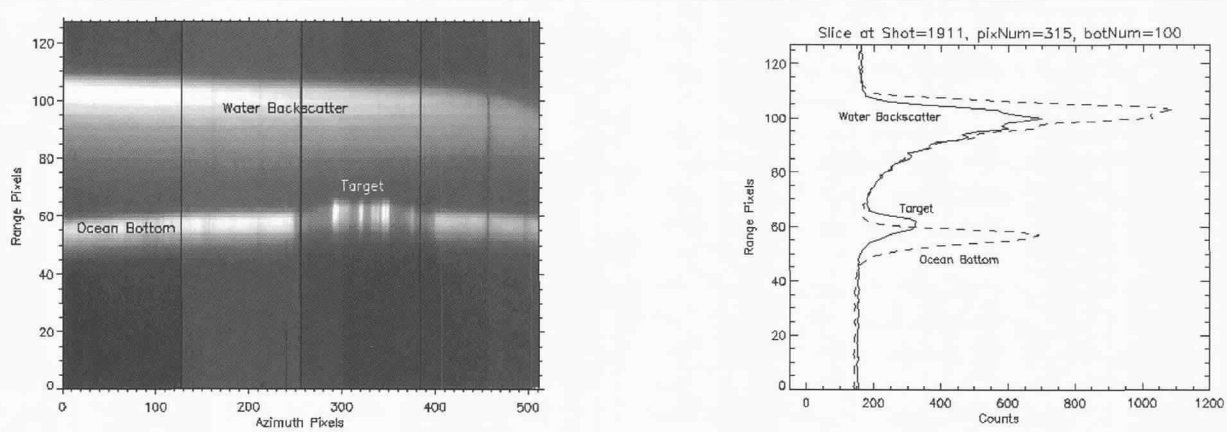
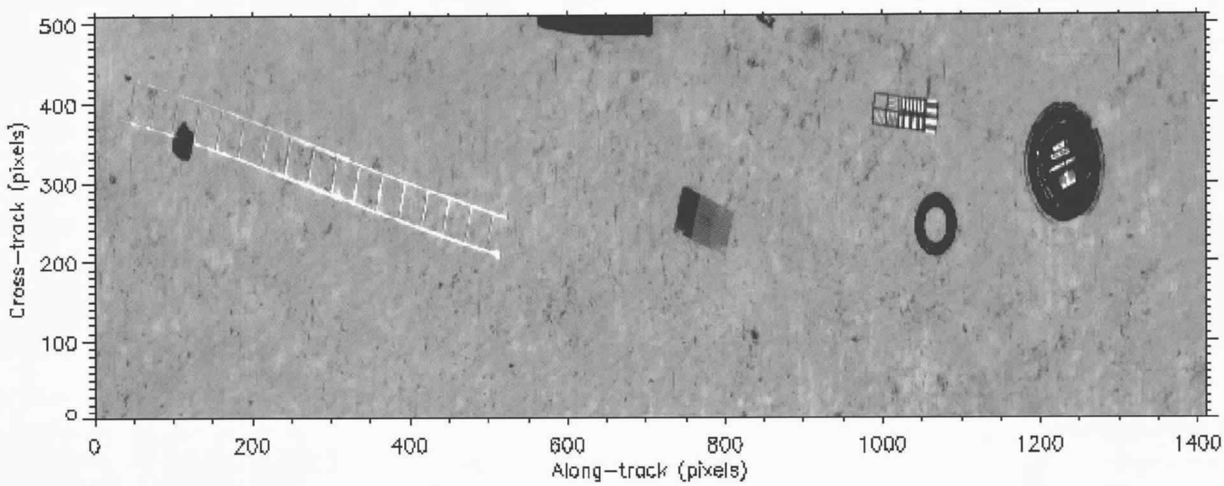


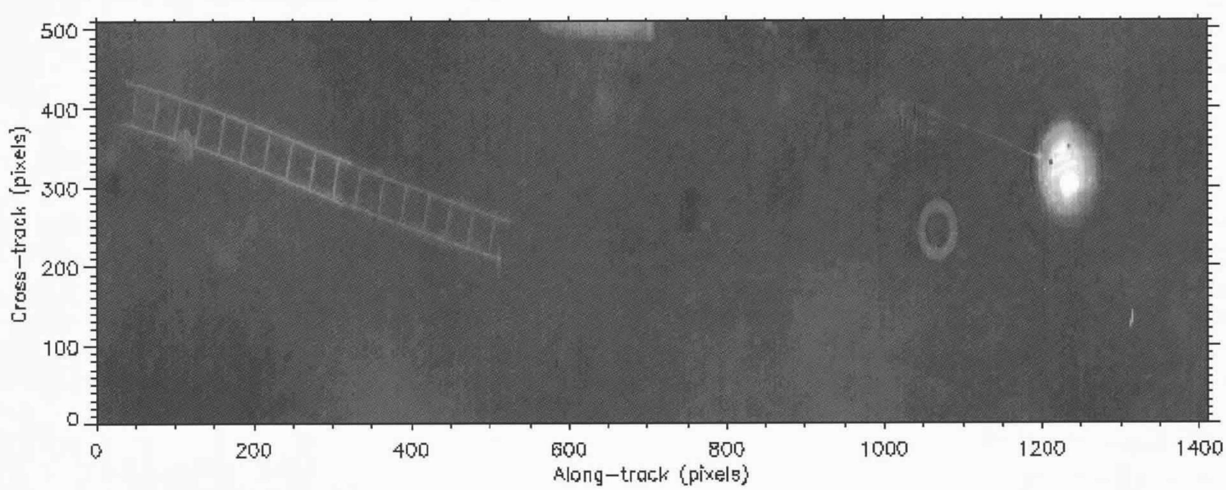
Figure 4. Single shot range-azimuth image (left), and range cut (right), showing exponential decay of water backscatter, range information from time of flight, and contrast information from amplitude of bottom return. The resulting multi-shot image scene is shown in Figure 5.

Figure 5. Contrast (a) and range (b) images at 24 foot depth, including ladder, contrast panel, resolution panel, tire, and truncated cone (30 inch diameter by 18 inch 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 (c).

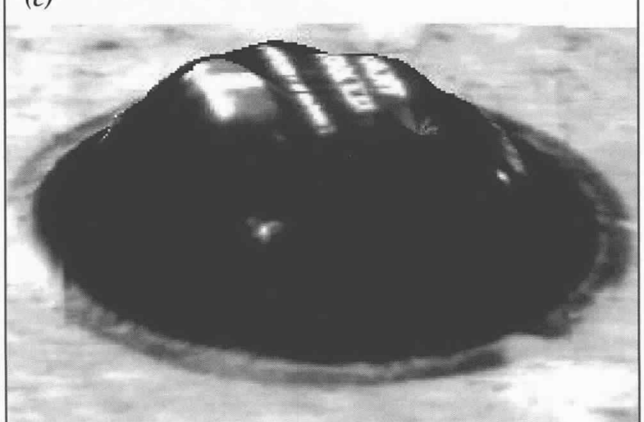
(a)



(b)



(c)



plier 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 seafloor. The input/output optical assemblies employ four-faceted mirrors, yielding four 90° scan lines per rotation of the drive shaft. Scan line (cross track) imagery is formed from the center 70° 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.

This sensor can be configured in several ways to

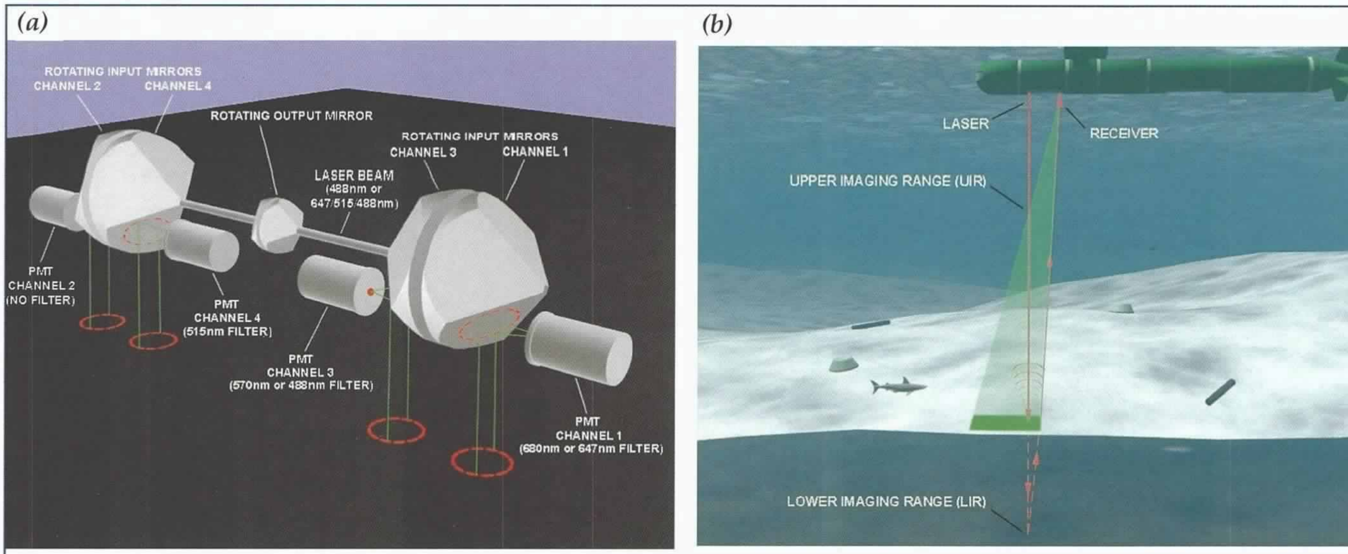


Figure 6. ***(a)*** *A simplified schematic diagram of the four-receiver LLS sensor used for FILLS or RGB-color imagery.* ***(b)*** *For each receiver, the upper imaging range (UIR) is the near range where the field of view of the scanner intersects the laser beam, while the lower imaging range (LIR) 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 771x Speed(knots)/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 x Altitude(m)/N_{pixel} where N_{pixel} (512, 1024, 2048, or 4096) is the number of pixels per 70° 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.*

acquire different types of data. In a fluorescence configuration designed to investigate coral reefs, an Argon ion laser is used 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 a second configuration, the laser is an Argon/Krypton mixed gas laser, which produces simultaneous outputs at 647 nm (red), 515 nm (green), and 488 nm (blue). When three of the receivers are fitted with matching filters, the data required to produce RGB color imagery can be obtained.

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 6b, the receiver spots on the sea floor are roughly rectangular in shape. 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

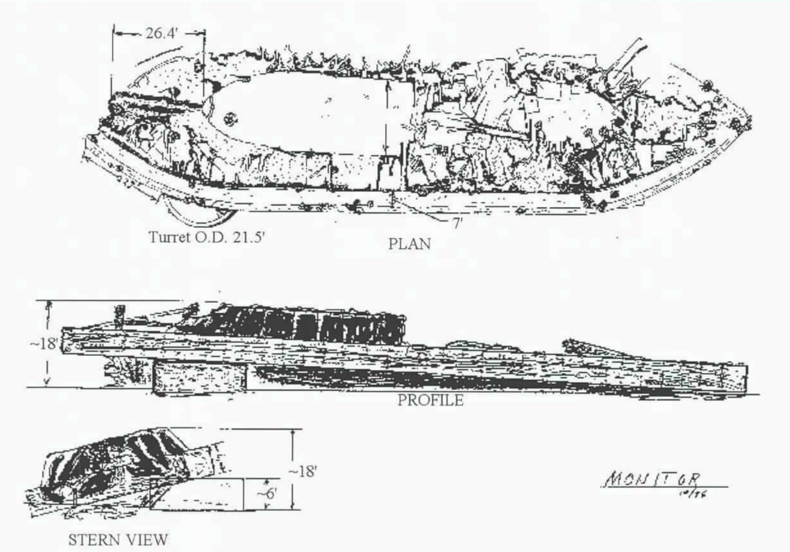


Figure 7. *A schematic of the hull of the* Monitor *as it rests on the seafloor.*

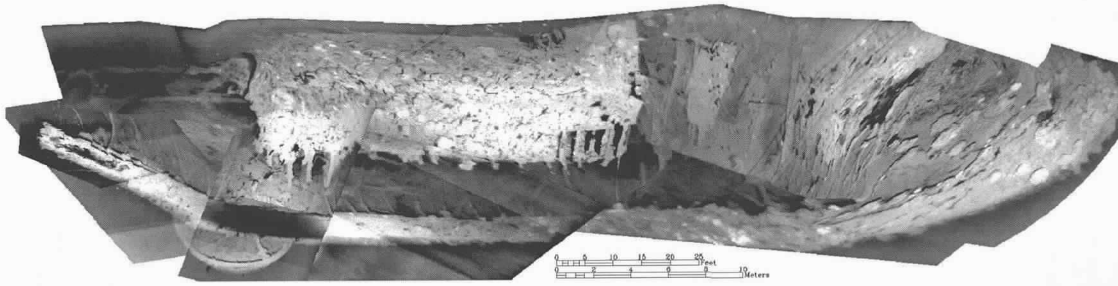


***Figure 8.** A mosaic of the remains of the* Monitor *taken from LLS imagery.*

ranges are set by water visibility conditions. Images that have been taken with the system under a variety of environmental conditions are presented next.

Monitor

In October 1996 the LLS sensor was used to image the famed Civil War ironclad *USS Monitor*. The *Monitor* presents significant imaging challenges, and 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 7 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 feet high and 7 feet 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 two missions of approximately one hour each.

Figure 8 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 9, 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 one of the benefits of the high intra-scene dynamic range provided by the 12 bit digitization.

(a) *(b)*

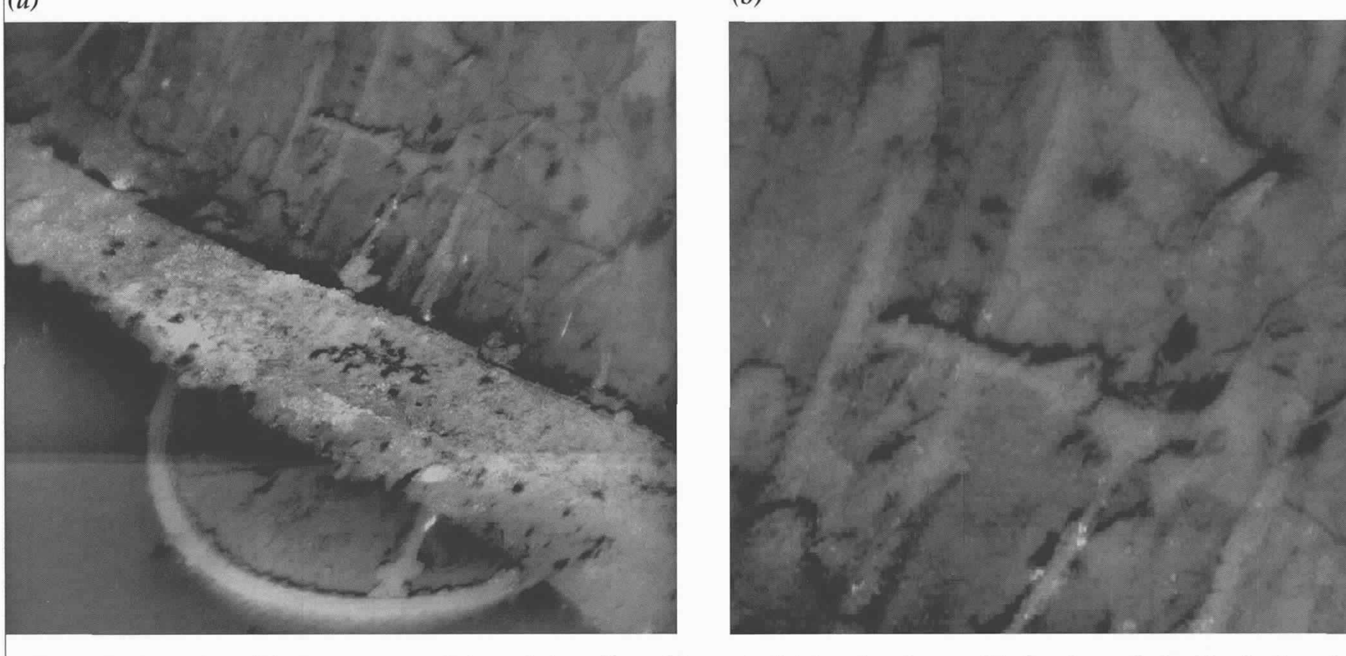


***Figure 9.** A portion of the turret, armor belt, and the collapsed lower hull **(a)** and a closeup **(b)** showing coiled cables in the collapsed lower hull.*

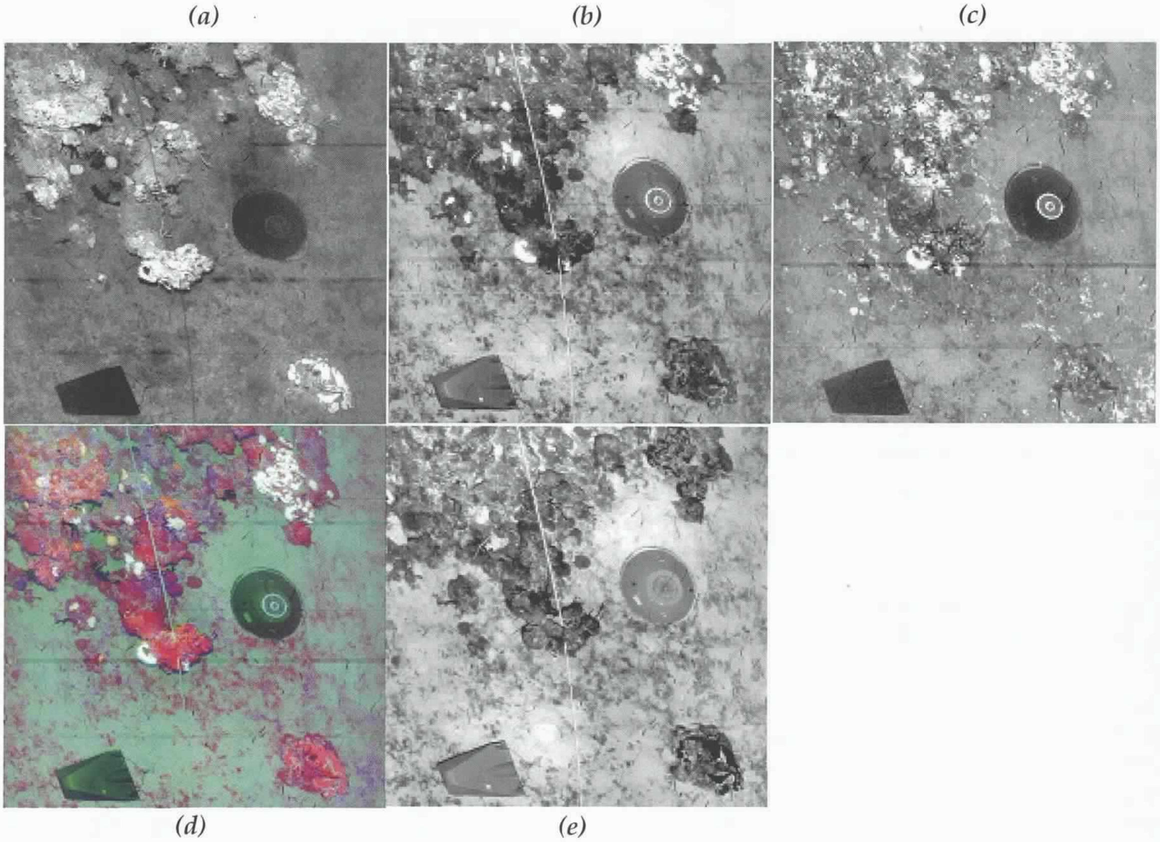


*Figure 10. The top row **(a-c)** shows images from the red, green, and yellow channels of the FILLS sensor. These are formed primarily from fluorescence stimulated by the 488 nm laser, although there is some leakage of reflected 488 nm light into the green channel. The bottom row compares the pseudocolor fluorescence image **(d)** with the corresponding image formed from reflected 488 nm laser light **(e)**.*

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 9b is a zoomed sub-image of Figure 9a, showing detail, including a coiled cable, in the lower hull rubble.

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 10 a-d shows FILLS imagery for the elastic scatter channel and each of the fluorescence channels. 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. Figure 11 illustrates an additional image of stromatolites collected with the system.

3D Sea Scan

The 3D Sea Scan (Figure 12), a very recently built system, has the capability, like STIL, of obtaining 3-dimensional images (Figures 13 and 14). Like LLS, it uses a scanning laser beam. However, in this case, instead of having a PMT for light detection, a one-dimensional CCD array is used. As in LLS, the 3D Sea Scan system scans a collimated laser beam from side to side. The volume 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 its 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 that, at its heart is an application of the principle of triangulation. For moderate altitudes: 3 m-5 m, the system can achieve excellent range resolution: 2

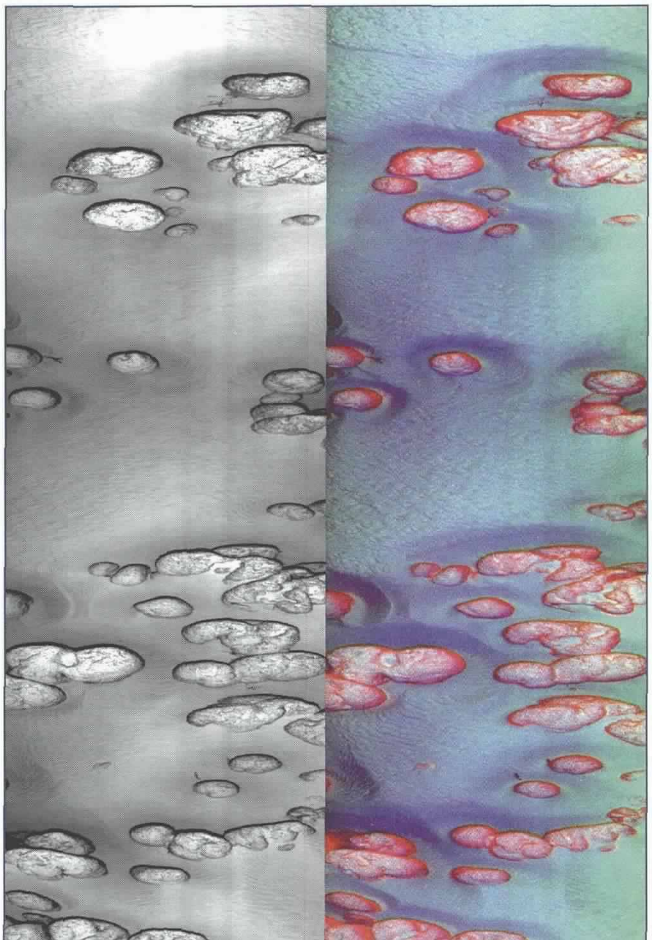


Figure 11. FILLS images of stromatolites in the vicinity of Lee Stocking Island. The left image is formed from elastically scattered light at 488 nm, the right image is a pseudo-color image created primarily from fluoresced light. It is evident, when stimulated by the 488 nm laser light, stromatolites produce significant red fluorescence signals. This imagery was acquired at 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.

mm-5 mm. The system uses source-receiver separation for both good image quality and also the triangulation scheme, which here are mutually compatible. 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 13 shows the result of processing data that were recorded when the system was towed over a field of turtle grass in the vicinity of Lee Stocking Island. Figure 14 shows a 3-dimensional image that was recorded as part of a U.S. Office of Naval Research (ONR) field program to monitor bottom scatter of acoustics and the temporal and spatial characteristics of the seafloor. Time evolving records of the bottom were

Figure 12. The 3D Sea Scan System being launched.

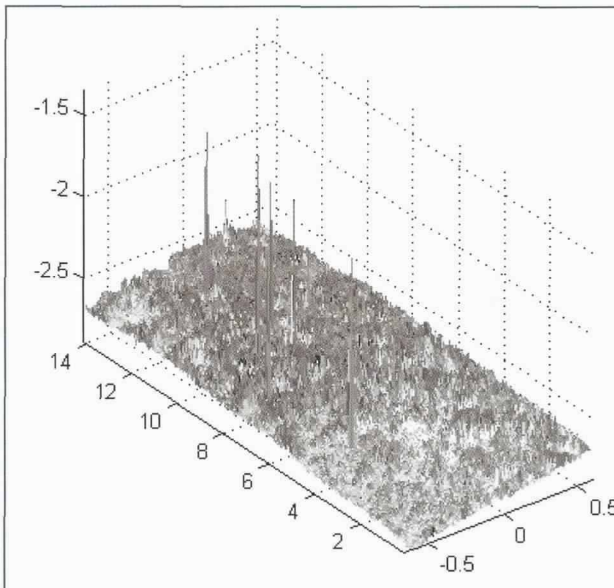


Figure 13. A 3-dimensional rendering of a field of turtle grass from Lee Stocking Island. All scales are in meters. Note that the seafloor in this area is white sand and that the grass is seen as the darker objects protruding out of the seafloor. The several large spikes are likely due to fish that were hovering over the seafloor.

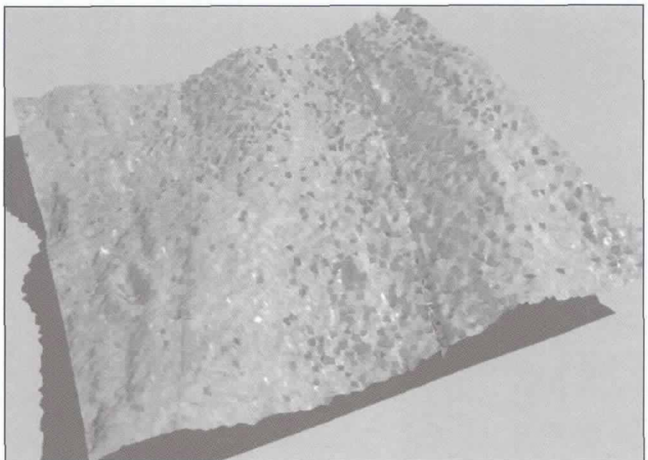


Figure 14. *A 1.4 x .85 meter field of view taken with the 3D Sea Scan system. For the purpose of acquiring this image, an underwater frame was developed which facilitated the precise positioning of the system over the seafloor. The system was suspended from the frame and translated precisely over this 1.4 meter track. The recorded data were analyzed to provide an estimate for both the reflectivity of the seafloor as well as topography. The images of these two parameters were then input into the Bryce system of computer rendering programs in order to provided 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. This image shows several underwater sand waves with an aggregation of larger stones in the depressions and finer sand at the crests.*

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 that is coupled with a point source. Both are "confocal" that is, in the same focal plane of a lens that is used both for illumination and also collection of images. There is a slight increase in resolution when using this method, but the primary advantage is the elimination of scattered light that is not confocal to either the laser source or the pinhole aperture. As such, underwater imaging systems could be developed which are monostatic and eliminate backscatter using this technique.

Finally, the very latest generation of optical components continues to create new areas of possibility for underwater optical imaging system design and fabrication. In the case of illumination, the introduction of more efficient blue-green lasers with adequate power now makes the fabrication of autonomous, battery powered, systems a reality. In the case of sensing hardware, new developments in the fabrication of multidimensional PMT arrays will create additional opportunities for approaching the ultimate sampling of the 3-dimensional temporally and spatially varying radiance for future generation systems.

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