Chapter 4
Active Underwater Imaging

4.1 Introduction

One of the main issues concerning diver visibility is that it is directly dependent on the availability of natural light. The theories developed and discussed in the last chapter, for the most part, are only applicable under ideal situations. In other words, they can be seen as a one-way propagation special case, where path radiance can be neglected or does not pose significant issues, such as those in the development of the new Secchi disk theory.

However, the convenience of natural light is not always available nor dependable from an operational standpoint. Also, the limited range of detection of the passive approach negates the usefulness of underwater EO systems at times, despite its higher resolution. Active EO imaging systems, like those of active sonar systems, can take advantage of extended ranges of detection and identification by applying various approaches to reduce (or discriminate against) mostly backscattered photons that enhance the range. Because of the similarities in principle between active EO and acoustical systems, and the wide-spread use of acoustical systems in underwater sensing applications, both are discussed in this chapter.

4.2 Active Electro-Optical Systems

Over the years, many approaches have been developed to increase visibility range underwater. They involve both civilian and military applications, including search and rescue, survey, inspection, mapping and research, target detection and identification, etc. Several review articles have covered these developments and approaches well from a historical prospective, such as Duntley (1963), Mertens (1970), papers in the AGARD lecture series, as well as recent reviews (Jaffe, McLean, and Strand, 2001; Kocak et al., 2008).

Generally, two issues hinder the visibility range underwater, and both are due to scattering by the medium and constituents within. Forward scattering leads to the spread of photons in small forward angles, resulting in blurring of the image. This is shown throughout various examples in the previous chapter.

While particle scattering typically introduces the type of degradation that is well known and well studied, both theory and measurements have shown that in very small angles, it is turbulence scattering that accounts for the majority of scattering contributions. This is the case not only in clean water situations, where the phenomena is more pronounced relative to those of particle scattering contributions, but is also evident in turbid waters, especially when biological activities are high and exopolymers are abundant (Passow and Alldredge, 1994). Backscattering impacts imaging system performance by reducing image contrast when an artificial light source is used for additional underwater illumination to compensate for the rapid loss of light with increasing depth. This is especially bad when the light source is close to the camera (Fig. 4.1). Unless the object of interest is self-illuminating (which is discussed in the previous chapter), including a light source with an underwater imaging system is critical for obtaining high-resolution images at extended ranges. Several methods have been developed to mitigate the backscattering issue, including separating the light source and receiver, range gating using the time-of-flight principle, synchronous scanning between the light and receivers, and modulated systems, especially non–line-of-sight (NLOS) imagers. These are sketched in Fig. 4.1. The range of detection of each approach is listed in the figure as a crude reference of system performance. Details of these approaches are discussed in the following sections.

4.2.1 Separation of source and receiver

The availability of natural light disappears very fast with depth, starting with the color red disappearing at about 15 ft, orange at 30 ft, yellow at 60 ft, and green at 80 ft, in clear ocean waters (McGraw-Hill Encyclopedia, 2002).

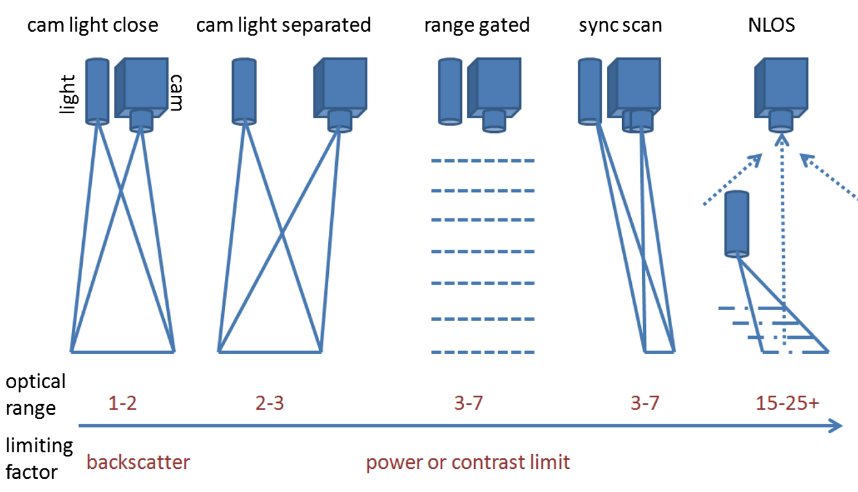


Figure 4.1 Comparison of various underwater imaging systems and maximum range. [Adapted from Jaffe, McLean, and Strand (2001).]

Artificial lights are usually used for photography and other EO imaging systems at greater depths, even though faint blue light can still be available. While it sounds simple enough, the importance of separating the light and the camera is not readily recognized by underwater photographers (Jaffe, McLean, and Strand, 2001) (see Fig. 4.2). This is essentially the same principle as not using the high beams while driving in heavy fog, as strongly backscattered photons cast a bright veil, reducing the visibility to effectively zero in no time.

The physics behind this observation can be traced back to the basic optical properties of ocean water in Chapter 2, where it is shown that elevated backscattering is caused by particulates in the water. Although backscattering is relatively weak compared to forward scattering, the close proximity to the source tends to compensate enough for the difference; Gershun's law describes an exponential reduction of the radiance from the light source over the imaging range. The net outcome is a veiling effect that could severely reduce contrast of the image.

By separating the source and the receiver, only the weak side-scattered photons will likely reach the receiver, while at the same time, the common volume intercepted by the source and receiver is much smaller than direct illumination, as shown in Fig. 4.3. While it is always a desired approach, it is not always convenient (or even possible) to significantly separate the source and the receiver of an active imaging system, especially considering the confined space of unmanned underwater vehicles.

Figure 4.2 U.S. Navy photographer training underwater. Notice that the light is away from the camera. (Courtesy of Wikipedia and U.S. Navy; photograph by Mass Communication Specialist 1st Class Jayme Pastoric.)

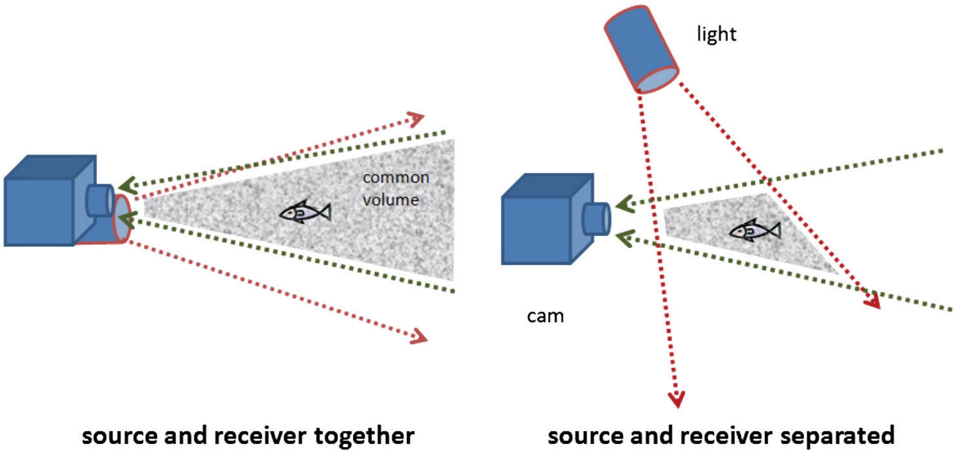


Figure 4.3 Separation of light and camera helps to reduce backscattering to achieve a better image, due to weak side scattering and less common volume.

4.2.2 Time of flight and range gating

With the introduction of short-pulsed lasers, it became possible to illuminate targets of interest with intense light, without the contamination of backscattered photons. This is accomplished by using the time-of-flight principle, as shown in Fig. 4.4.

It is easy to see that the time of flight for the two photons to reach the detector is different—longer for the black circle, which has been scattered multiple times, and shorter for the red circle, which goes directly into the receiver (ballistic). If the source is a pulsed laser and the receiver is synchronized to the pulsed source, then by opening and closing the receiver at the right time, it is possible to shut out (or gate out) the unwanted (i.e., scattered, especially backscattered) photons to achieve a better image. This is more clearly explained in Fig. 4.5.

The gate of the receiver is kept closed when pulsed light travels toward the intended target or range. This prevents backscattered photons from entering the receiver, causing a reduction in image contrast. Once the controller decides

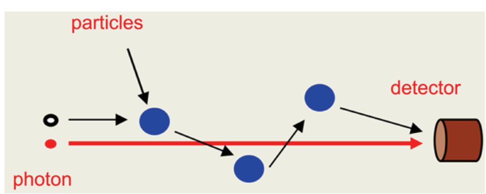


Figure 4.4 Time-of-flight sketch showing that scattered photons (black circle) travel a longer path and therefore take more time to reach the receiver, compared to ballistic photons (red circle).

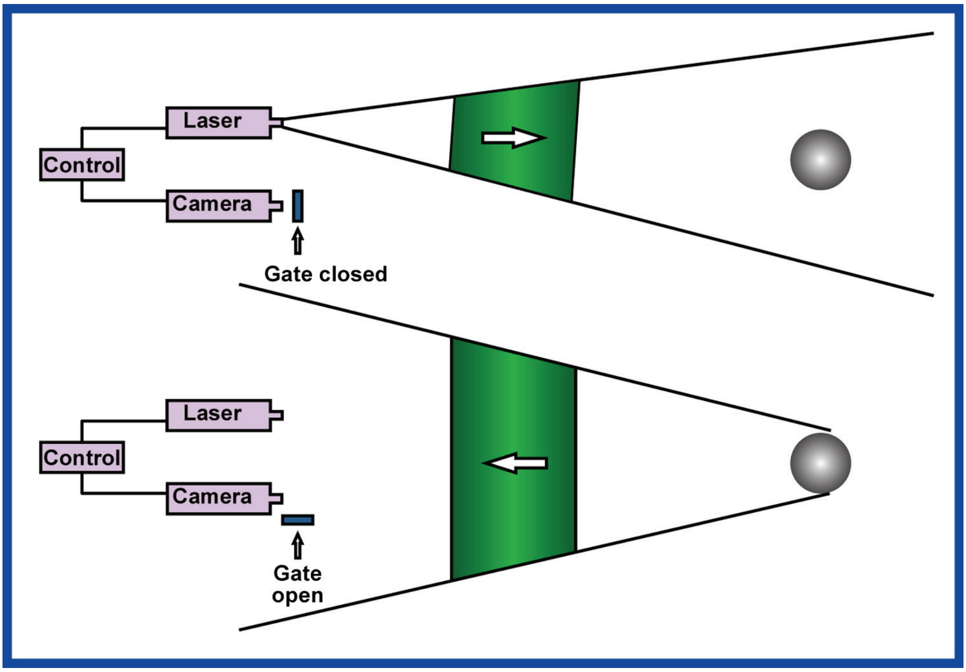
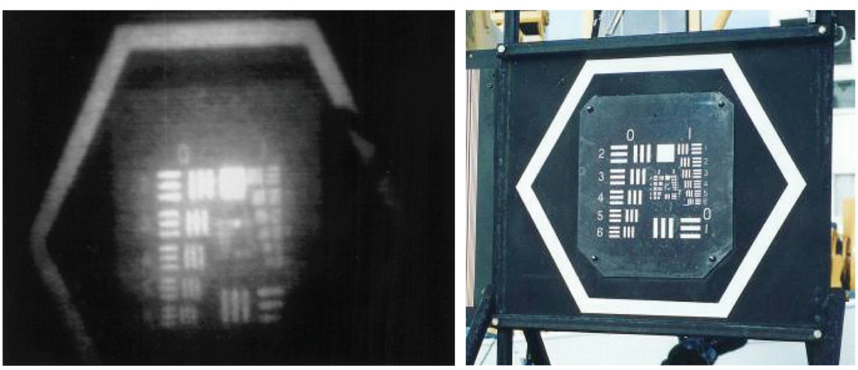


Figure 4.5 Range-gating camera principle. (Courtesy of Georges R. Fournier.)

that the desired reflected or backscattered photons are approaching from the desired range, by calculating the time it takes for the photon to travel, it opens the gate of the receiver for the right photons to enter (Fig. 4.5). This way, only photons from a desired range can be collected to form an image, thus the term *range gating*. A sample image collected by such a system is shown in Fig. 4.6,



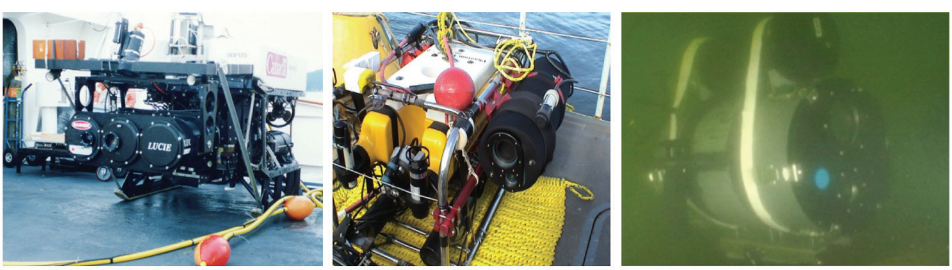
(a) (b)

Figure 4.6 (a) Example of a range-gated image at 8.6-m range underwater. The visibility is 3 m. (b) Target in air. (Courtesy of Georges R. Fournier.)

(a) (b)

Figure 4.7 Sample images of a Secchi disk (a) in air and (b) in turbid water at two attenuation lengths (OD, beam-*c* valued at 1.2 m^{-1}). (Courtesy of U.S. NRL.)

which demonstrates a 3× increased range when compared to passive vision systems under similar resolution. As a comparison, a passive Secchi image is shown in Fig. 4.7 at two attenuation lengths [same as optical depth (OD)] underwater. The system used to acquire the image in Fig. 4.6(a) is the Laser Underwater Camera Image Enhancer (LUCIE), in its second generation, fitted for an underwater remotely operated vehicle (ROV), shown in Fig. 4.8. LUCIE involves 20 years of effort from Defence Research Development Canada (DRDC) (Fournier et al., 1993). It utilizes a unique feature that employs a high repetition rate (22.5 kHz) of the pulsed signal (2-W 532 nm, 7-ns pulse, 3-ns gate, on LUCIE2) at any given range, to increase the signal-to-noise ratio (SNR) by on-chip averaging in the intensified CCD camera. The output is 30 Hz (video rate). A newer version of the system, fitted for use by divers as a handheld unit, has been implemented and is shown in Fig.4.8. It is self-contained with a battery, and is capable of 90 min of continuous operation, with a lower-power laser for eye safety (600 mW, 1-ns pulse,



(a) (b) (c)

Figure 4.8 Three generations of LUCIE: (a) LUCIE1 (1990–1996); (b) LUCIE2 (1998–2006); and (c) handheld LUCIE (2006–2009). (Courtesy of Georges R. Fournier.)

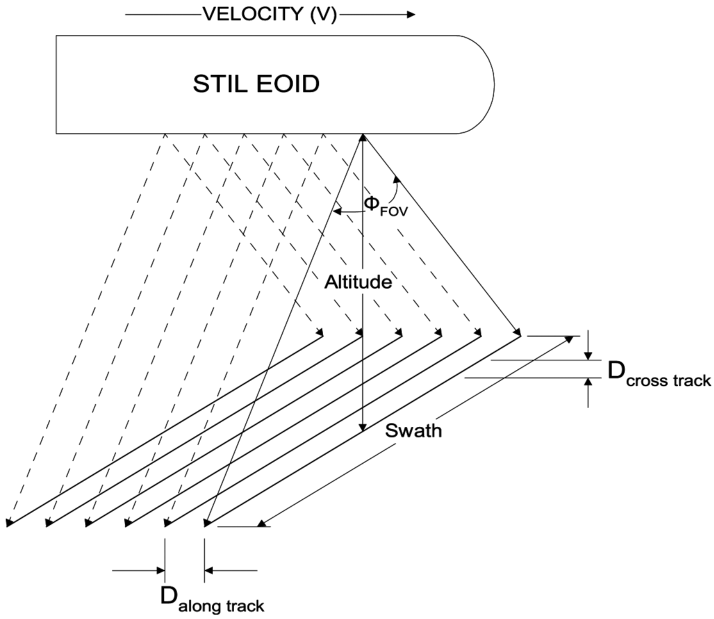


Figure 4.9 Sketch of Streak Tube Imaging Lidar (STIL) operational concept. [Figure adapted from Jaffe, McLean, and Strand (2001).]

5-ns gate, and 20-kHz repetition). Automatic ranging is achieved using a sonar altimeter system.

Another example of a successful underwater gated imaging system is the streak tube imaging lidar (STIL) system (Bowker and Lubard, 1993), developed by Arete Associates (Northridge, California) for underwater EO identification (EOID) applications. A fan-shaped beam of pulsed laser source is used for illumination, perpendicular to the track of a moving platform (Fig. 4.9). The along-track resolution can be adjusted by the speed of the moving platform and the laser repetition rate. Not only is the time-of-flight information recorded per pulse, but also the intensity of backscattering from the target, at operational resolution on the order of centimeters (Fig. 4.10) (Jaffe, McLean, and Strand, 2001). The image quality and ability to retrieve range information makes this a favorable candidate for many underwater applications.

4.2.3 Synchronous scan: spatial filtering

Another major approach to underwater EO imaging is the synchronous scan method. It is also known as the laser line scanner (LLS) approach, since it uses a highly collimated beam (cw laser) to illuminate each point of interest of the image, typically via a rotating mirror, while the collector optics focuses with a very narrow field of view (FOV) on the light beam synchronously via a