Laser scanning imaging system for underwater robotics vehicle

Xu, Lin

2007

Xu, L. (2007). Laser scanning imaging system for underwater robotics vehicle. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/6553>

<https://doi.org/10.32657/10356/6553>

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LASER SCANNING IMAGING SYSTEM FOR
UNDERWATER ROBOTICS VEHICLE

XU LIN

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UNDERWATER ROBOTICS VEHICLE**

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SCHOOL OF MECHANICAL & AEROSPACE ENGINEERING

2007

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Laser Scanning Imaging System for Underwater Robotics Vehicle

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A thesis submitted to the Nanyang Technological University
in fulfilment of the requirement for the degree of
Doctor of Philosophy

2007

Abstract

In recent years, underwater robotics vehicles (URVs), including remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), are growing rapidly in deployment for both commercial and military applications. Among various imaging approaches used in these vehicles, optical vision has shown great advantages in intuitive representation and extremely high resolution, when compared with a popular alternative like acoustic imaging. Unfortunately, optical images are severely degraded due to the absorption and scattering of light in turbid water environments. Performance of a conventional camera system directly depends on the turbidity of water.

Green laser has been used as an active light source because of its good transmittance in water and its high output power. At present, novel lighting and imaging systems, such as laser galvanometer scanning systems and range-gated systems have shown some achievements in minimizing light scattering effects. However, their unwieldy sizes and high power consumptions limit their usages on small URVs. This thesis discusses a low-powered and low-speed scanning scheme, which has an adjustable illumination volume to fit various water turbidities. The illumination beam can be concentrated to improve image signal-to-noise ratio in turbid water, and expanded to improve frame update rate in clear water. The scheme has advantages in simple structure, compact size, and low power consumption.

An illumination model is developed to analyze the relationship between light flux, illumination volume, and water turbidity. It focuses on highly turbid water condition, and assumes that forward and backward scattered fluxes uniformly fill all forward and backward directions. Light propagation is divided into two stages: from light source to object, and from object to camera. The light flux in each stage is regarded as a linear superposition of transmitted, forward-scattered, and backscattered components, which are individually calculated with volume scattering function and Bouguer's law.

The model differs from existing models as it considers geometric parameters in an illumination scene. It quantitatively reveals how illumination volume affects the distributions of flux components. When a light beam is being expanded, the total flux received by a camera increases, and backscattered component increases faster than the correctly transmitted (or desired) component. When a wide illumination beam is used in turbid water, the signal strength of the scattered noise may exceed that of the desired signal component. This makes the objects undetectable.

The model has been verified with experimental measurements in a 0.6 meter long water tank. The theoretical expectations were consistent with the experimental measurements when water attenuation coefficient is great than 2.0 m^{-1} . Due to the assumption of uniform scattering, the model is only valid in highly turbid water. It was applied to the configuration of a prototype of laser scanning system. Various beam sizes were tested and their output images were evaluated by the MTF (modulation transfer function) assessment. The image contrast indexes obtained with a thin beam illumination (cross-sectional radius 0.01 m) were twice of that with a wide beam illumination (radius 0.03 m).

In conclusion, this research studied the effect of illumination volume on camera imaging. A laser scanning system was shown to be able to improve signal-to-noise. Small illumination beam is able to reduce scattering and improving image quality in highly turbid water environments.

Acknowledgement

First of all, I would like to express my sincere gratitude to my graduate supervisor, Associate Professor Gerald Seet, and co-supervisor, Associate Professor Martin Adams, for their invaluable help on the research work described herein, as well as throughout my study at Nanyang Technological University.

My heartfelt thanks are also due to Dr. He Duo-Min, a research fellow in Robotics Research Center (RRC). His suggestions and professional experiences gave me much help in widening my insight and keeping correct orientation in the research field.

I owe my appreciation to my colleague, Mr. Tan Ching Seong. Although He worked on a different project, range-gated imaging, he provided much helpful advice on my research. I am also thankful to the staffs in RRC. Without their assistance, many tasks would have been impossible.

Finally, I thank my family for their supports.

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List of Symbols

A	Absorbance
P	Flux, (W)
E	Radiant exitance, or irradiance, area distribution of flux, (W/ m ²)
I	Radiant intensity, solid angle distribution of flux, (W/sr)
V	Volume of medium, (m ³)
Ω	Solid angle, (sr)
θ	Planar angle of the cone, corresponding to the solid angle Ω
ρ	Reflection coefficient
λ	Wavelength of light, (nm)
c	Attenuation coefficient, (m ⁻¹)
a	Absorption coefficient, (m ⁻¹)
b	Scattering coefficient, (m ⁻¹)
b_b	Backscattering coefficient, (m ⁻¹)
b_f	Forward-scattering coefficient, (m ⁻¹)
L	Distance from light source to object, (m)
l	Distance from light source to scattering volume
R	Cross-sectional radius of light beam, (m)
r	Cross-sectional radius of scattering volume
D	Separation between light source and camera, (m)
H	Radius of camera pupil, (m)

Abbreviations

AL	Attenuation Length
AUV	Autonomous Underwater Vehicle
BRDF	Bidirectional Reflectance Distribution Function
CCD	Charge-Coupled Device
CLAHE	Contrast-Limited Adaptive Histogram Equalization
ESF	Edge Spread Function
FOV	Field Of View
FWHM	Full Width Half Maximum
He-Ne	Helium Neon
IDT	Image Dissector Tube
IEEE	Institute of Electrical and Electronics Engineers
LASER	Light Amplification by Stimulated Emission of Radiation
LSF	Line Spread Function
LIDAR	LIght Detection And Ranging
MC	Modulated Contrast
MCP	Micro-Channel Plate
MTF	Modulation Transfer Function
OD	Optical Density
PMT	Photomultiplier Tube
ROV	Remotely Operated Vehicle
PSNR	Peak Signal to Noise Ratio
SPIE	Society of Photo-Instrumentation and Optical Engineering
TVI	Time Varying Intensity
USAF	United States Air Force
URV	Underwater Robotics Vehicle
UWLIS	Underwater Laser Imaging System
VSF	Volume Scattering Function

Chapter 1 Introduction

Nowadays we are capable of investigating surface of the earth and exploring outer space, but we have very limited knowledge about deep sea world. About 70% of surface area of the earth is covered by oceans, and enormous wealth and resources are buried in seas. As the world's population and resource consumption increase, more and more attention has been focused on the oceans. At present, techniques for undersea development are still very limited and awkward. Intelligent underwater vehicles are main platforms to implement underwater fieldworks.

Acoustic transmitters and receivers are widely used in underwater applications. They are suitable for long distance detections and navigation, but they are unable to provide high resolution images. Like human eyes, optical imaging is an irreplaceable aspect in information acquisition. Unfortunately, visible light is severely attenuated in a turbid water medium. The signal damping is essentially related to the properties of the water, dissolved matters, and suspended particles. Due to effects of absorption and scattering, capturing a good image in turbid water is more difficult than that in air.

A number of underwater vision techniques came forth from 1990s. Many laboratory instruments were developed, and trials were carried out in experimental water tanks and in real sea conditions. In most experiments, weights, sizes, and power-consumptions of imaging devices were not of concern because all devices are installed on big ships or submarines. Now small underwater vehicles have become popular particularly in underwater exploration due to their low operation costs and flexible performances. An

imaging system on a small vehicle has to meet the requirements of compact size, low power-consumption, as well as low cost.

Previous experiences show that the type of illumination directly affects scattered noises in images. In order to maximize vision range, an imaging system must properly arrange light sources and cameras. The illumination method and water medium are two most important factors in image systems.

1.1 Underwater robotics vehicle

Underwater robotics vehicles (URVs) are intelligent devices that are driven through the water by propulsion systems, controlled and piloted by onboard computers or remote operators, and maneuverable in three dimensions (von Alt, 1994). They include remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs). Both the ROV and AUV are equipped with thrusters, sensors, computers, and power batteries. An ROV is usually attached to a platform or mother ship by a long cable. It can be controlled with video screens and joysticks by human operators from surface vessels. An AUV operates without such a cord and it is guided primarily by an inertial reference system. To correct for the inevitable drift off course, an AUV has to communicate with the mother ship regularly. Onboard sensors and controllers on ROV and AUV are able to implement spatial and time series measurements in real time, and collect data for further offline processing as well.

URVs are necessary underwater tools in deep and hazardous sea operations. They are able to dive to depths of 300 meters or more, and provide high reliability, efficiency and safety in underwater environments. URVs are replacing human divers in ocean exploration, object searching, equipment maintenance, etc. Their missions are usually classified into several

categories: hydrological survey, seafloor exploration, salvage search, inspection, fishery, and military applications (Bellingham, 1992). A hydrological survey focuses on the physical and chemical properties of the water. It collects data such as water temperature, conductivity, turbidity, turbulence and other ocean properties. Seafloor survey is a geologically based mission, which maps the bottom surface or takes rock, mineral, or sediment samples. Wreck discovery and localization are important search missions for salvage and archeological purposes. Military applications include underwater scouting, maintenance of construction and equipment. The use of URVs continues to grow rapidly. The number of URVs has grown from almost none 25 years ago, to more than 3,000 worldwide (Ouellette, 2002).

Figure 1. The small URV in RRC

URVs have different shapes, sizes, and weights in their applications. Their weights vary from tens kilograms to several tons. For example, the UROV 7K developed by the Japan Marine Science and Technology Center (JAMSTEC) is 2,700 kg (Murashima et al., 1999), while the small URV in Robotics Research Center (RRC), Nanyang Technological University, is only 100 kg with a compact size (1.0 x 1.0 x 0.5 meters, length x width x height).

Sensors are important parts of an URV. They allow URV to know outside environment and movement status. For example, sonar or vision sensors help URV to recognize underwater environment; inertial sensors and gyros measure velocities and accelerations of URV; navigation and positioning sensors guide URV to a designed route. Sensors can be classified as active and passive sensors according to their working principles. An active sensor, such as active sonar, emits detection waves first, and then receives and analyzes the reflected waves. Its detection range directly depends on the distance that the wave can travel before being attenuated or scattered. A passive sensor does not emit such detection waves, and it collects signals spreading in ambient environment. The performances of sensors are usually influenced by the propagation of waves. Both electromagnetic waves and acoustic waves are attenuated in water medium.

1.2 Attenuation ratios of physical waves in water media

Electromagnetic and acoustic sensors are the most popular and mature techniques in the world. The attenuations of electromagnetic and acoustic waves in clean water are shown in Figure 2 (Ogawa, 2000). Ultrasonic wave has very low attenuation when its frequency is lower than 100 kHz. Accordingly, ultrasonic signal can spread long distance in water. This property makes sonar (frequency range of wave: 10 - 50 kHz) very popular in underwater object detections (Mitson, 1984). In contrast, electromagnetic waves have high attenuation ratio, so electromagnetic signals disappear quickly in water medium. Fortunately, the attenuation of visible light is low when compared with other electromagnetic waves. This gives visible light good capabilities of imaging and communication in short-middle ranges in water.

Figure 2. Attenuation ratios of electromagnetic and ultrasonic waves in clean water

Acoustic waves are widely used in underwater applications because of their good propagation capabilities. Their applications mainly focus on URV navigation and object detection.

In navigation, a vehicle is guided by human operators or control units to reach its expected destinations. The position and dynamic states of the vehicle, such as distance, speed, and acceleration, need to be detected by navigation sensors. An acoustic positioning system consists of several pairs of transmitter and receiver. In a common sonar system, acoustic wave is emitted by a transmitter, reflected back by seabed, and then detected by a receiver. The distance between the sonar and the seabed is obtained by counting the transmission time of acoustic wave. Similarly an object and its distance can be detected in the same method.

Besides implementing depth extraction and obstacle detection, acoustic waves can be applied in visual images and non-destructive inspection (Charlesworth, 2001). For

example, ultrasonography is a mature medical technical for viscera diagnosis. In medical ultrasonic scanning, ultrasonic pulses are sent into a human body, and the echoes are determined by the tissue density and organs. The delays and strengths of the echoes are used to construct visual images (Bushberg, 1996). However, the ultrasonic image is different from the normal appearance of the object, and the image resolution is inherently restricted by the wavelength of the ultrasonic wave. Because of these disadvantages, ultrasonic imaging has many limitations in quantitative analysis (Sun, Horng, Lin, & Wang, 1996).

The capability of object detection is required in most URV tasks such as underwater environment discovery, wreck search, and structure maintenance. Optical vision is one of important detection methods. It provides the most natural interpretation of outside environments to human eyes (Castleman, 1979). It also provides extremely high resolution (Narasimhan, 2004). Optical vision is widely used in all kinds of intelligent vehicles. In simple applications, human operators control remote vehicles with the help of live videos. In advanced applications, computers installed on the vehicles replaces human to analyze the video image and navigate the vehicle automatically. With the development of electrical industry, digital video cameras have become affordable and standard equipments on almost all intelligent vehicles. A typical vision system is comprised of cameras, video digitizers, computers, and image processing software.

Obtaining high-quality images is a basic requirement in a vision system. At present, cameras are the most common tools for recording optical signals and forming visual pictures. However, visible light experiences severe attenuation during its propagation in a turbid water medium. Performance of a conventional underwater camera system depends on

the visibility of the underwater environment, which is about 100 - 200 feet in very clean water (Funk, Bryant, & Heckman, 1972). Nowadays, new equipments, such as laser illumination, intensified cameras, and range-gated schemes, are developed to extend vision range. Moreover, image processing techniques, such as image enhancement and reconstruction, are also employed to improve the capability of feature extraction and objects identification.

Light propagation is significantly influenced by the effects of absorption and scattering due to suspending particles in water. In the process of absorption, light energy is transferred into a different form such as thermal vibration. Photons disappear in the transformation. Accordingly, the optical flux received by a camera decreases, and output images become dark. Scattering means that photons are deflected from their initial trajectories. The photons do not disappear, but they would fall onto inappropriate locations at the camera imager. Therefore, the effect of scattering distorts or blurs output images.

Visibility is severely degraded due to the effects of absorption and scattering in turbid water. The following figure shows the influences of absorption and scattering on image quality. The pictures in Figure 3 are taken by a monochromatic camera under a floodlight illumination. The bar-pattern target in the left image is placed in clean water. The details in the picture are vivid, and the patterns edges are sharp. When the target is placed in turbid water, the effects of absorption and scattering make the picture (the right one) blurred. Most details of the patterns are lost.

Figure 3. Images in different water conditions

Water medium has complex optical characteristics such as scattering, absorption, refraction, diffraction, and polarization. The scattering is a primary factor affecting image quality. In Figure 3, the water turbidity is quantitatively labeled by an attenuation coefficient c , which contains absorption and scattering.

1.3 Optical properties of the water

Visible light is an electromagnetic wave. In water, the phenomena of light absorption and scattering are the interaction results of photon and water medium. Practical water, such as deep sea water or seashore water, is mostly an isotropic homogeneous medium (Arst, Haltrin, & Arnone, 2002). In such a dielectric medium, atoms can scatter the light - redirecting it without otherwise altering it. At the same time, atoms absorb the light. During the two processes, some light energy is transformed to thermal energy via collisions due to random atomic motion (Buiteveld, Hakvoort, & Donze, 1994).

1.3.1 Absorption

Absorption is a process of transform of light energy into a different form such as thermal energy, i.e., the heat motion of the molecules. In the process that a photon hits a molecule of

the absorbing matter, the photon disappears, and the molecule absorbs the energy of the photon, and rises to a higher vibrational state. Finally the energy from the photon is dissipated as heat within the medium. The overall effect of absorption is a reduction in the intensity of the light beam traversing the medium.

The absorption of pure water is strongly wavelength dependent, as shown in Figure 4 (Buiteveld et al., 1994; Pope & Fry, 1997). Pure water also displays absorption bands: the green-blue light (wavelength 450 - 550 nm) is relatively slightly absorbed.

Figure 4. Absorption coefficient in pure water

The wavelength dependency of absorption widely exists in natural materials. Some materials that are transparent to visible light, like glass, show absorption (opaque) in other wavelength regions like ultraviolet and infrared. On the other hand, some materials like rubbers are opaque for visible light but transparent for infrared.

A relationship between the absorption of light in a purely absorbing medium and the thickness of the medium was defined by the Lambert-Bouguer law (or Beer-Lambert-Bouguer law) in 1760.

$$\frac{dI}{I} = a \cdot dL \quad (1)$$

The equation describes how each successive layer (dL) of the medium absorbs the same fraction (dI/I) of the incident intensity (I) for an absorption coefficient constant (a).

Let the incident intensity is I_0 , the transmitted intensity I through a distance L will be:

$$I = I_0 e^{-aL} \quad (2)$$

This is a popular form of the Lambert-Bouguer law.

The absorption coefficient a is interpreted as the probability that a photon will be absorbed by the medium per unit length. The reciprocal of the absorption coefficient is known as the absorption length (absorption length = $1/a$). It is the distance required for the intensity of the beam to fall to $1/e$ of the initial intensity.

Equation (2) sometimes is expressed in base 10 logarithms, the transmitted intensity is $I = I_0 10^{-KL}$. The constant, K , is known as the extinction coefficient. It is conceptually same as the absorption coefficient, a . The extinction coefficient is linearly related to the absorption coefficient by a factor of 0.434 (i.e., $\log_{10} e$).

In optical industry, the Equation $I = I_0 10^{-KL}$ is often written in an equivalent form:

$$A = KL = \log_{10} \frac{I_0}{I} \quad (3)$$

A is called absorbance. Its unit is optical density (OD). OD is usually used to mark the absorbance of a density filter. For example, 1 OD means that only 10% radiance ($I = 0.1I_0$) remains after the light passes through the filter.

The Lambert-Bouguer law has two limitations although it is widely used in optical absorption.

- (1) The light entering the medium must be monochromatic and perfectly collimated, and
- (2) The medium itself must be homogeneous and uniform.

Not only water molecules, the particulate matters suspended in aquatic environments, such as the phytoplankton, quartz particles, organic and inorganic detritus (Haltrin & Shybanov, 2000) also cause absorption. The total particulate absorption is the sum of individual contributions by different matters. The wavelength dependency of absorption is greatly related to these matters in water. For example, blue and red light are absorbed by chlorophyll for photosynthesis (Tassan, Mitchell, Stramski, & Bricaud, 1997).

1.3.2 Scattering

A simple definition of scattering is any divergence from a straight-line path. In the underwater realm, light can either be diffracted by particles whose dimensions are of the order of the wavelength of the light, or be refracted by particulate matter which has a different index of refraction than the media. Unlike absorption, scattering is weakly wavelength dependent.

In an underwater environment, the scattered energy is much greater than that absorbed. Therefore scattering is regarded as the primary factor that determines the propagation of light. The characteristics of water medium and suspending particles cause various types of scattering. There are three mature models explaining underwater scattering: Rayleigh scattering, Mie scattering, and Raman scattering.

(1) Rayleigh scattering

Rayleigh scattering refers to the scattering of light off the molecules of air, and can be extended to scattering from particles up to about a tenth of the wavelength of the light (McCartney, 1976). This scattering is the main reason for the sky being blue. Light from the sun is scattered by molecules in the atmosphere to all directions, including towards the observer at the earth's surface. Since scattering is more effective for light at shorter wavelengths (the blue side of the spectrum), the scattered light is predominantly blue. This makes the sun itself appear red/orange, since the blue light is scattered in other directions than towards the observer. This is best visible when the sun is at the horizon. The reason for this is that when the sun is at the horizon, light travels a large distance through the atmosphere when compared to the situation where the sun is right above the observer (Marcel, 1948).

Rayleigh scattering increases with the fourth power of the frequency and is more effective at short wavelengths. For the case of N particles which are small size relative to the wavelength, isotropic and distributed at random, the radiant intensity I in the direction θ is (Jerlov, 1968):

$$I = I_0 \frac{8\pi^4 N \alpha^2}{\lambda^4 R^2} (1 + \cos^2 \theta) \quad (4)$$

where α is the polarizability of particles,

λ is the wavelength of light,

and R is distance from scatterer.

Rayleigh scattering can be considered to be elastic scattering since the energies of scattered photons are not changed. If the scattered photons have either higher or lower photon energy, the process is called Raman scattering. Usually this kind of scattering involves exciting some vibrational mode of the molecules, giving lower scattered photon energy, or scattering off an excited vibrational state of a molecule which adds its vibrational energy to the incident photon.

(2) Raman scattering

Raman scattering is the scattering in which the wavelength (or photon energy) of the scattered light is different from the wavelength of the incident light. Raman scattering is inelastic scattering. The incident photons interact with the molecules in such a way that energy is either gained or lost so that the scattered photons are shifted in frequency. In the process, energy from the incident photons is transferred to the molecule, leaving the molecule in a higher vibrational state and the photon at lower energy. Scattering of a photon off a molecule in a higher vibrational state will result in scattered photons with higher energy and a molecule in a lower vibrational state. Scattered intensities are low resulting in difficult detection of the Raman Effect. Raman scattering does not play a significant role in underwater visibility.

Like Rayleigh scattering, the Raman scattering depends upon the polarization of the molecules. For polarized molecules, the incident photon energy can excite vibrational modes of the molecules, yielding scattered photons which are diminished in energy by the amount of the vibrational transition energies. A spectral analysis of the scattered light under these circumstances will reveal spectral satellite lines below the Rayleigh scattering peak at the incident frequency. Such lines are called “Stokes lines”. If there is significant excitation of vibrational excited states of the scattering molecules, then it is also possible to observe scattering at frequencies above the incident frequency as the vibrational energy is added to the incident photon energy. These lines, generally weaker, are called anti-Stokes lines.

Although finding some application in vibrational spectroscopy of molecules, the use of direct infrared sources for such spectroscopy is usually much easier. Raman spectroscopy has found some application in remote monitoring for pollutants. For example, the scattering produced by a laser beam directed on the plume from an industrial smokestack can be used to monitor the effluent for levels of molecules which will produce recognizable Raman lines.

Raman scattering can also involve rotational transitions of the molecules from which the scattering occurs. Thornton and Rex picture a photon of energy slightly higher than the energy separation of two levels being scattered, with the excess energy released in the form of a photon of lower energy. Since this is a two-photon process, the selection rule is $\Delta J = \pm 2$ for rotational Raman transitions. The sketch in the following figure is an idealized depiction of a Raman line produced by interaction of a photon with a diatomic molecule for which the rotational energy levels depend upon one moment of inertia. The

upper electronic state of such a molecule can have different levels of rotational and vibrational energy. In this case the upper state is shown as being in rotational state, J , with scattering associated with an incoming photon at energy matching the $J+2$ state.

Figure 5. Photon energy in Raman scattering

Since the Raman Effect depends upon the polarizability of the molecule, it can be observed for molecules which have no net dipole moment and therefore produce no pure rotational spectrum. This process can yield information about the moment of inertia and hence the structure of the molecule.

Due to the rotational and vibrational energy differences, an intense monochromatic light source (such as laser) gives the scattered light one or more sidebands. This is potentially very useful for remote sensing, since the sideband frequencies contain information about the scattering medium which could be useful for identification. Current projects envisage Raman scattering as a tool for identification of mineral forms on Mars (Sharma, Wang, & Haskin, 2005). Such remote sensing could become a major tool in planetary exploration.

(3) Mie scattering

The scattering from molecules and very tiny particles ($<1/10$ wavelength) is predominantly Rayleigh scattering. For particle sizes larger than the wavelength of the incident light, Mie scattering predominates.

Figure 6. Direction dependency of scattering

Mie scattering is not (or hardly) wavelength dependent. In air, the scattered light will look white or light bluish, depending on the size of the scattering particles.

Mie scattering produces a pattern like an antenna lobe, with a sharper and more intense forward lobe for larger particles. The direction of the scattered light peaks forward, as is shown in Figure 6. An example of this directional scattering is shown in the photograph of the Duane wreck (Figure 7): there is a white halo around the sun. Sunlight is scattered by particles in the water. Since this scattering is mainly forward directed, it appears as a halo around the sun. Since there is hardly wavelength dependency, this halo is white.

Figure 7. Diver at wreck of Duane at 30m/110ft, Key Largo, Florida

(4) Scattering in the practical seawater

Due to the characteristics of the particles, the seawater principally appears in Mie and Rayleigh scattering. The effect of Raman scattering is slight and negligible. The water molecules and suspending particles are regarded as independent scatterers whose scattered intensities do not interfere with each other. Independent scattering is also termed as incoherent scattering.

Independent scattering does not imply that the incident light is scattered only once by a single particle. In fact, the multiple scattering frequently takes place. Any given particle is exposed not only to the incident light but also light scattered by other particles. A simple analogy is the inter-reflections between scene points, as shown in Figure 8. A single photon experiences enormous interactions with the particles. The multiple scattering causes the single scattering functions in Rayleigh and Mie scattering to get smoother and less directional.

Figure 8. The propagation of a single photon in turbid water

The optical intensity in multiple scattering is the sum of different orders of scattering (Bryukhanova & Samokhvalov, 2000):

$$I(L) = I^{(1)}(L) + I^{(2)}(L) + \dots + I^{(i)}(L)$$

where $I^{(i)}$ is intensity under the i^{th} order scattering,

L is the length of the optical path.

The flux in the first order scattering is the primary magnitude of the total scattering. Therefore, many researches use the first order scattering, i.e., the single scattering, to model the scattering in practical water.

According to appearance, scattering is usually classified as forward and backward scattering. Referring to Figure 9, it is called forward scattering when the scattering angle θ is less than 90° , or backscattering when θ is greater than 90° .

Figure 9. Forward and backward scattering

1.3.3 Attenuation - the sum of absorption and scattering

Bouguer's law indicates the exponential decrease of light energy in an absorption medium. The conclusion can also be extended to light scattering. When light is passing through gas, liquid, or solid matters, it is absorbed and scattered by the medium. In the process of absorption, light energy is transformed into thermal energy, and the incident photon disappears. In scattering, light energy does not disappear, and the light ray is forced to deviate from a straight trajectory by one or more molecules and particles. The term of attenuation is used to cover both absorption and scattering (Mobley, 1994). After going through path length L , the light intensity that is remaining its initial trajectory direction is

$$I = I_0 e^{-aL} e^{-bL} = I_0 e^{-(a+b)L} \quad (5)$$

where a , b are the absorption and scattering coefficient.

The attenuation coefficient, c , is defined as the sum of coefficient a and b ,

$$c = a + b \quad (6)$$

Due to the suspending particles, real seawaters usually represent strong scattering behavior. The scattering coefficient, b , is much higher than the absorption coefficient, a . A table below lists some measured data from the waters off the South Island of New Zealand (Williams, Colley, & Vincent, 1995).

Table 1. The optical properties of water masses at the South Island of New Zealand

Water mass	a (m^{-1})	b (m^{-1})	c (m^{-1})
Inshore/coastal	0.098	0.312	0.411
West coast	0.086	0.294	0.380
South western oceanic	0.056	0.168	0.224
Sub-antarctic	0.033	0.113	0.148

From Equation (5) and (6), the equivalent expression of light attenuation is usually written as:

$$I = I_0 e^{-cL} \quad (7)$$

where I is the intensity of the light after traveling a distance d , (W/m^2)

L is the light path length in medium, (m)

I_0 is the initial intensity of light, (W/m^2)

and c is attenuation coefficient, ($1/\text{m}$)

The attenuation coefficient is mainly determined by water itself, dissolved matter (organic or inorganic), and suspended particle (organic or inorganic). The total attenuation is a superposition of all factors.

$$c = c_{\text{water}} + c_{\text{dissolved}} + c_{\text{particle}} \quad (8)$$

Attenuation length (AL) usually describes the dependence of light intensities on distance. It is the distance along the traveling path where the intensity of light falls to $1/e$ of its initial value. AL is the reciprocal of attenuation c .

$$AL = \frac{1}{c}$$

When the scattering and absorption are considered separately, the processes are defined as scattering length and absorption length. They are the basic indices to present the visibility of environment or the vision performance of a vision system.

Equation (7) only indicates that the light follows its original trajectory. The scattered light does not disappear. Some scattered light may fall onto the camera imager. Since they are

not reflected from the expected object, they are classified as noise. The amount of scattering is determined by water condition and illumination light. Most researches in underwater imaging aim to eliminate or reduce the scattered light, especially the backscattered light. The laser scanning system is one of the solutions to suppress the scattering noise. This thesis will discuss the scattered light in detail whilst considering the water condition and the geometrical scheme of the vision system.

1.3.4 Polarization

Polarization is an important characteristic of light. Light waves are transverse waves. The vibration of a transverse wave takes place in a direction perpendicular to the direction of propagation, and rotational symmetry about the direction of propagation does not exist. This lack of symmetry is called polarization (Meltzer, 1965). Each light wave is completely polarized. In the natural world, a light source produces millions of such waves, and each wave has a random orientation of its polarization (Breon, Tanre, Lecomte, & Herman, 1995). As a result, the totality of light acts as an unpolarized beam. For example, the natural light from the sun is unpolarized.

Polarization may occur in an underwater environment. When a beam of light passes through a suspension of small particles, the light will be scattered by the particles. If the particles are very much smaller than the wavelength of the light, the scattered light will be plane polarized. For different wavelengths, polarization maxima occur at different angles.

The character of polarization state changing in scattering media can be used to enhance underwater visibility. When a polarized light beam passes through the turbid water, the polarization states of the photons are changed in the interaction of scattering and absorption. However, the unscattered photons maintain their original polarization states (Morgan,

Khong, & Somekh, 1995). Once the polarization state is discriminated by the polarimeter instruments, the unscattered light is separated from the scattered light. Image resolution and object recognition are improved by extracting the unscattered or weakly scattered light (Giakos et al., 2004; Miasnikov & Kondranin, 1992; Tonebon S. & Reuter R., 2000).

The optical properties of water, including absorption, scattering, and polarization, are discussed briefly. Light scattering is dominant in real seawater. Mie is usually applied in real sea water where the suspending particles have large sizes (diameter $> 1 \mu\text{m}$). It is independent of the wavelength of the incident light. In clean water, there is a sharp optical transparency (i.e., low absorption) window in the blue-green, wavelength from 450 to 550nm. The green light usually is used because of its low absorption characteristics.

1.4 Organization of the thesis

Optical imaging has significant advantages for its intuitive output and extreme high resolution. Live video has been widely used in underwater applications. However, one significant obstacle in underwater optical imaging is that the image quality is severely degraded due to scattering of light by a turbid water environment. New techniques, such as laser illumination and gated cameras, have been employed to overcome the problem. This thesis focuses on a laser scanning method. The illumination volume of light beam is a crucial basis in a continuous illumination scene. It is directly related to the amount of scattered noise and light power.

Attenuation of visible light essentially depends on the characteristics of water medium. The first chapter describes the inherent optical properties of water, primarily the absorption and scattering (Rayleigh, Raman, and Mie). In underwater light propagation,

illumination light loses some energy due to the absorption of water medium, and changes the transmission direction due to the phenomenon of scattering. Investigations have shown that the flux of scattered light is several times higher than that absorbed in seawaters. To improve the imaging capability of an underwater vision system, the effective solution is to eliminate or reduce the scattering.

Current techniques of reducing scattered noises include line scanning imaging and range-gated imaging. They will be reviewed in Chapter 2. Laser beam with galvanometer scanning, structure lighting, and interferometric projection use continuous illuminations, while the range-gated systems employ pulsed illuminations. These laboratorial setups have produced good results in extending visibility range. However, they cannot be installed on the small URV platforms because of their large sizes and high power consumption. This thesis focuses on a flexible beam scanning scheme. As the water turbidity is variable in natural environments, the illumination volume in a scanning system is alterable to effectively make use of illumination power. The scanning system can also balance the image quality and scanning time. For example, to reduce scattered noises in turbid water, the illumination beam will be concentrated, and the time of scanning a scene will be increased. In clean water, the beam is expanded to speed up the scanning. The method requires only a low-powered laser and conventional camera, so it can be used on small URVs to replace high power consumptive floodlights.

Chapter 3 will propose a mathematic model to analyze the relationship between illumination volume and scattered light in a reflection scene. Objects in the model are assumed Lambertian. Light propagation is divided into two stages: from light source to object, and from object to camera. The optical signal in each stage is regarded as a linear superposition of three components, named as direct-transmitted, forward-scattered, and

backscattered components. The effects of the geometric diameter of illumination beam are analyzed in the calculations of these components. The results will quantitatively reveal how illumination volume affects the distributions of light components.

The theoretical calculations will be verified with experimental results in Chapter 4. A low-powered green laser (wavelength 532 nm, 5 milliwatts output) acts as a light source. Three cross-sectional radii of the illumination beam are tested: 0.01 m, 0.02 m, and 0.03 m. The underwater environment is simulated in a 0.6 meter-long water tank, and the water turbidity is adjusted by mixing Mylanta antacid (a dense milky liquid) into clean water. A monochromatic CCD camera and a frame grabber capture images and convert image pixel values to optical irradiance. The measured results are compared with the theoretical expectations.

Small illumination volume helps to reduce the scattered noise, and then improve image quality. However, a still and thin beam only illuminates a very small area. In order to obtain a wide and full view, an imaging system has to conduct a thin beam to scan whole target. Small illumination volume requires more scans and time to obtain a full frame. A prototype of laser scanning system will be demonstrated in Chapter 5. In the setup, a mirror conducts a laser beam to implement a two-dimensional scanning. Camera capture action is synchronized with the rotation of the mirror. Each horizontal scan produces a stripe image, which is then registered together. The performance of the vision system will be evaluated by its output images. Three kinds of image assessment are introduced. They are subjective evaluation, pixel differences comparison, and MTF (Modulation Transfer Function) assessment. Laser scanning method is a hardware solution to make objects detectable, and software enhancement is able to give images good appearances to satisfy

some special requirements. CLAHE (Contrast-Limited Adaptive Histogram Equalization) will be applied to experimental images.

This thesis focuses on the effect of illumination volume on camera imaging. A laser scanning system is shown to be able to improve signal-to-noise ratio and make dim objects detectable, and that its illumination beam plays an important role in reducing scattered noise and improving image quality in turbid water environments. The works and conclusions will be summarized in Chapter 6.

Chapter 2 Vision Systems for Underwater Applications

With the developments of electrical and optical instruments, techniques for improving underwater vision capability bloomed from 1990s. They include non-imaging and optical imaging methods. Non-imaging methods are usually based on acoustic techniques. The invisible acoustic signals are converted to visible pictures in special formats through computer processing. Optical imaging methods are able to provide intuitive and extremely high resolution outputs. They include conventional camera systems, synchronous scanning, range gating, and polarization controls (Caimi, 1996).

Underwater imaging techniques will be reviewed in this chapter. Film camera and digital camera are the basic devices for image acquisition. Optical intensifiers, such as MCP, (micro-channel plate), are able to amplify weak optical signals. They greatly extend vision range in low-light underwater environments. They have benefited both conventional camera systems and special imaging systems.

In turbid seawaters, image noise primarily comes from the scattering of light. However, conventional camera systems and image intensifiers are unable to remove scattered noises. Novel optical configurations, such as laser scanning, structured light projection and range-gated system, are coming forth. Their operating principles, hardware configurations, advantages and disadvantages will be discussed in this chapter. The reviews will help us to understand the vision system design on URV platforms.

2.1 Camera and image intensifier

In the 18th century, people knew that certain chemicals darken when exposed to the sun. In 1727, Johann H. Schulze, a German scientist, proved that silver nitrate becomes dark due to sunlight and not by temperature. His observations paved the way towards photography (Wood, 1997). Today the film photography still employs silver halides to record and store optical information.

With the developments of the electrical and electronic industries, electro-optical imaging sensors are replacing conventional films gradually. They collect and measure optical radiation using semiconductor elements. Light source is also improved. A conventional light source only provides plain illumination. An advanced light source is able to modulate the light frequency and amplitude. This makes it possible to measure the range from the detector to the target by demodulating the time information.

Electro-optical sensors represent great convenience and economy because they can immediately convert optical signals to electrical signals. Among various electro-optical sensors, CCD cameras are very popular because of their high resolutions and low costs. They are usually employed in normal illumination conditions. To extend their applications, CCD cameras may work with optical intensifiers, such as MCP, to obtain images in extreme dark environments.

2.1.1 CCD (Charge Coupled Device)

CCD is an acronym for Charge Coupled Device. The principle of charge coupling is widely used in electronic devices to perform many functions. In optical applications, the device works by electron production due to photon excitation. Visible light hits a semiconductor

material and the quantum of energy frees a bound electron. Each absorbed photon creates an electron-hole pair. Either the electrons or holes can be stored in a potential well, and then read off by varying the voltage with time.

Figure 10. Cross section through CCD pixels

The architecture of a CCD has three basic functions: charge collection, charge transfer, and conversion of charge into a measurable voltage. The charge created at a pixel site is proportional to the incident light level. The aggregate effect of all the pixels is to produce a spatially sampled representation of continuous image scenes.

CCD is very efficient at light-to-electron conversion. It is able to measure very faint light. The light-to-electron conversion is linear. This means: twice as much signal indicates a twice as bright object. A pixel has limited capability to collect the charge. If too much light falls, the charge may overflow onto neighboring pixels. This is called “saturation”. This characteristic limits the dynamic range of CCD. A CCD designed for low-light detection is unable to work at a bright environment for long time without protection. In computer images, the pixel value is usually digitized in the range from 0 to 255, where 0 indicates black (no light is presented), and 255 means complete white (the cell of CCD is saturated due to the stimulation of light).

Since the CCD is a very sensitive instrument, it may generate “artificial” signal by itself, even when there is no light stimulation. This kind of signal acts as noise, and the most well known one is called dark current (Balabin, Borovkov, & Chernouss, 2003). Dark current is due to the thermal motion of the material of CCD. The atoms themselves tend to knock off some electrons during their thermal vibrations. The electrons may randomly fall into the potential wells of CCD pixels without the assistance of a photon. The phenomenon causes dark current noise.

All CCD chips produce dark current. Long exposure (several seconds or longer) in dark environment may cause high level of noise in images. Fortunately, the exposure time for a normal picture or video is very short occurring in several milli-seconds or less. In a normal illumination condition, there is a lot of light entering the camera which overwhelms the dark current. As temperature is the main causation of dark current, some special cameras are coupled with a cooling mechanism to restrain the phenomenon of dark current.

The charge of electron-hole pair is determined with incident photons, whose energies are related to the wavelength of light. A CCD has different spectral responses to wavelengths. Like human eyes, most CCD cameras are designed to be sensitive to green-blue light of wavelength from 400 nm to 600 nm. Some special cameras have sensitivities to light at different wavelengths. For example, an infrared camera can form images with the invisible infrared light (wavelength from 800 nm to 1000 nm).

2.1.2 Optical intensifier

In dark environments, such as deep seas, the ambient illumination is so dim that it cannot trigger CCD. To deal with weak light radiation, some intensifiers are mounted in front of

CCD camera to boost the optical signals. The micro-channel plate (MCP) is one of well-known intensifiers.

Figure 11. Structure and principle of MCP

A conventional MCP is used for two-dimensional secondary electron multiplication. It consists of more than ten thousand lead-glass micro-capillaries and has two electrodes on each side. Due to the presence of an electric field along the channel, the electrons or photons injected into the MCP are accelerated until they in turn hit the wall. The number of electrons emitted at each impact is a strong function of incident electron energy. When an electron or energetic photon impacts on the MCP, several electrons will be ejected from the wall of the micro-channel. The impacts take place repeatedly. Eventually the electrons or photons are multiplied by between ten thousand to one million times (Sakamoto T., Takahashi K., & Takeuchi S., 1995). Consequently the weak light can be seen by the CCD camera. The sensitivity of the camera is markedly improved in this way.

Photodetector and photomultiplier tubes are other extremely sensitive detectors for the measurement of light radiation. They convert the individual quanta of light, photons, first

into electric currents and then into digital photocounts (Sica, 1999). For example, a photodiode generates a high number of electron-hole pairs with a small number of photons. Such is the case of the avalanche photodiode (APD), where each generated electron-hole pair is accelerated by an electric field, thus gaining enough energy to ionize other carriers, and freeing other electron-hole pairs similar to an avalanche phenomenon. These kinds of sensors are suitable for a point or small-area measurement because of their small acceptor windows.

According to the principle of MCP, high voltage is required to boost the multiplication of electrons. Therefore, the uses of MCP are usually limited to larger underwater vehicles which are able to provide enough electric power supply.

In turbid seawaters, the scattered light exists over the whole field of view. Both scattered noise and desired signal can be received by a camera and indiscriminately intensified by a MCP. In this condition, although a MCP can make dim scenes bright enough, it cannot improve image details. Other techniques are required to distinguish objects placed in dim and turbid water.

An imaging system includes camera, light source, and the layout of instruments. To eliminate or reduce scattered noise, all elements in the imaging system must be properly configured. Conventional imaging system and novel techniques are suitable for different applications because of their characteristics.

2.2 Imaging in underwater environments

There are many kinds of techniques applied to underwater imaging. Active light source directly determines the magnitude and distribution of light, including reflected signal and scattered noise. Illumination source and configuration are often used to name an imaging system.

Typical illumination and imaging methods are classified in Figure 12. There are conventional imaging with wide illumination, line scanning, interferometry imaging, and range gating system. They have been researched in laboratorial and practical applications.

Figure 12. Optical imaging in underwater environments

2.2.1 Conventional illumination

To get a satisfactory image, a vision system must consider light source, ambient light, optical distortion, and object surface property. At present, cameras have good performance. An off-the-shelf camera is able to provide excellent images in normal.

In an underwater imaging system, the image quality relies on both the camera and the illumination. The amount and quality of lighting are important. Natural sunlight is a good illumination source, but it is available only at or near the surface of sea water, and it is also severely affected by cloudy or foggy weathers. In most underwater conditions, especially in deep or shallow water, active lighting units are equipped to provide artificial illuminations.

There are two types of generic lamp, the incandescent filament lamp, and the gas discharge lamp. The incandescent, or filament bulb is probably the most common lighting type used in domestic housing. It works using a simple principle that if some materials got hot enough, they would start to glow. In a light bulb, an electric current passes through the filament, and heats it up to a point where the filament glows brightly. The amount of light produced by an incandescent bulb is proportional to the heating of the filament (i.e., proportional to the current flowing through the filament). An incandescent lamp produces a broad, continuous spectrum of light with the emphasis on the red wavelengths of light. It is well suited for use with color cameras.

A gas discharge bulb normally comprises a sealed glass or quartz outer envelope, inside of which is a gaseous vapor. The big difference over the incandescent bulb is that there is no filament. Two inert metal electrodes are fitted inside the glass envelope and separated by a gap. When a sufficiently high voltage is put across the two electrodes, an electrical discharge occurs between the two electrodes, just like a miniature lightning strike. The gaseous vapor inside the bulb absorbs the energy of discharge arc, and then emits light of a different color wavelength. Some gas discharge lamps emit discrete line spectra, and others emit a broad spectral distribution or many discrete wavelengths. They are often used for critical color video applications because their spectrum does not cover the whole

range of visible colors. The most common gas discharge lamp in domestic use is fluorescent tube. It has a fluorescent coating inside the long glass tube to provide a nominal white light output, and to filter out potentially harmful ultra-violet wavelengths.

Incandescent lamps have low efficiency in energy conversion from electrical power to visible light. Only 10% input power is transformed to light, and others are transformed to heat (Hooker, 2001). In contrast, discharge lamps have high efficiency, and they convert over 50% of the input energy into visible light. Both incandescent and discharge lamps provide wide illumination, and their typical input powers are from 100W to 1,000W in underwater applications (Kongsberg, 1997). They are not the ideal light sources for small underwater vehicles.

2.2.2 Laser scanning imaging

Laser scanning systems employ thin laser beams to illuminate and scan objects. They direct a laser beam to cooperate with conventional television cameras. The scan speed and image processing are limited with the speed of camera (30 frames per second). A full frame is obtained by registering scanning images together. The update rate of the full frame is as low as one frame per second.

There are two significant advantages in laser scanning schemes. First, they have long vision ranges. The illumination light can transmit over a long distance because the energy of light is concentrated in a small volume. Secondly, the small illumination volume helps to reduce the production of scattering.

(1) Time Varying Intensity (TVI) System

The Visibility Laboratory in University of California built a prototype laser imaging system named the Time Varying Intensity (TVI) system (Austin, Duntley, Ensminger, Petzold, & Smith, 1991). The TVI system was able to produce high quality images through turbid water by means of time encoded reflected light transmitted by scattering. It consisted of a compact battery operated scanning unit, an underwater receiver unit, and a control / image-storage / display unit.

Figure 13. TVI system in the Visibility Laboratory (1991)

The scanner unit scans the underwater scene with the laser beam in a manner similar to a television raster. It is positioned within a few meters of the target and aimed at the desired portion of the scene to be imaged. It can be carried by a human diver or a remotely operated vehicle. The scanner sends out synchronizing pulses and then illuminates the target with a television-like raster scan. The synchronizing pulses transmit through the water directly to a receiver at a remote location. Light from the raster scan of the laser is reflected from the

target to an optical receiver, also at the remote location. The reflected light from the target is time encoded.

In the hardware configuration, the laser scanner and the receiver unit are separated away. They are synchronized with the pulses sent by the scanner. The separation helps to reduce the backscattering, but makes the structure complicated. The scanner contains a 6 milliwatts HeNe (Helium-Neon) laser with wavelength of 632.8 nanometers. The receiver unit has two appropriately filtered photomultiplier tubes (PMT) and associated electronics to detect the sync pulse and reflected laser signal. Although the light (wavelength 632.8nm) has high absorption rate in water, the system has a long vision range in excess of 20 attenuation lengths (from target to receiver).

The TVI system has significant advantages over conventional imaging system. Its resolution capability equals or exceeds that of film cameras. It requires very much less total lights in the water.

The TVI research team determines the strength of received video signal with the equation:

$$N = P_l \rho \frac{H_R^2}{4} \frac{\Delta t}{q} \eta_R(\lambda) \left\{ \frac{e^{-c(\lambda)(l_1+l_2)}}{l_2^2} \left[1 + \frac{K(\lambda)l_2}{2\pi} e^{(c(\lambda)-K(\lambda))l_2} \right] \right\} \quad (9)$$

where N = the number of electrons per resolution element comprising the receiver photomultiplier current,

P_l = laser output power in continuous wave, (i.e., the input signal),

ρ = target reflectance,

H_R = effective diameter of receiver,

Δt = interval of time the laser scanner irradiates each resolution element,

q = charge on an electron,

η_R = conversion efficiency of opto-electronic device

l_1 = laser scanner-to-target distance,

l_2 = target-to-receiver distance,

$c(\lambda)$ = volume attenuation coefficient,

$K(\lambda)$ = diffuse attenuation coefficient for irradiance,

λ = wavelength of illumination light.

The amount of received photons are determined by all elements in their lightpath, including the light source (output power, P_l , illumination duration, Δt), the target (reflectance, ρ), the receiver (size of collector, D_R), and water medium. The photons are classified into direct transmitted photon and scattered photon. The direct transmitted photon is exponentially attenuated by the water medium. According to the Inverse Square Law, that is a source spreads its influence equally in surface of sphere, the energy of photon is also inversely proportional to the square of the target-to-receiver distance. The two processes are expressed in $e^{-c(l_1+l_2)}/l_2^2$. The energy of scattered photon has more complicate expression.

Besides the above two processes, it is also related to the diffuse coefficient, $K(\lambda)$, and the

path length, l_2 . That is the fraction of $\frac{e^{-c(\lambda)(l_1+l_2)}}{l_2^2} \frac{K(\lambda)l_2}{2\pi} e^{(c(\lambda)-K(\lambda))l_2}$ in the mathematical

equation. The total result is a linear superposition of direct-transmitted and scattered energies.

In the conversion of photon-electron, the current produced by an opto-electronic device is determined by the conversion efficiency, η_R , and the charge on an electron, q .

In all underwater imaging systems, the elements that affected the output of sensor includes light source, water medium, target, and receiver. This mathematical model demonstrates a typical calculation of signal acquisition. Although other imaging systems are using completely different illumination settings and receivers, they use similar considerations in their calculation of light flux.

(2) Synchronous-scanning underwater laser imaging system

An integrative synchronous-scanning underwater laser imaging system (UWLIS) was built by the Lawrence Livermore National Laboratory (Kulp, Garvis, Kennedy, Salmon, & Cooper, 1993). It has the capability of rapid two-dimensional scanning, like TV raster. The system employs a 7 watts argon ion laser in conjunction with a galvanometrically-driven scanner and an image-dissector tube receiver.

Figure 14. UWLIS in the Lawrence Livermore National Laboratory (1992)

A pair of galvanometrically-driven mirror directs the movement of a laser beam. Each mirror produces the horizontal and vertical deflection respectively. The combination of the

two actions performs a two-dimensional raster scanning (Figure 14). To extend the vision range, the laser concentrates optical energy into an extremely thin beam. An image dissector tube (IDT) detects the reflected light. IDC is used to convert photons to electrical signals. Now it is replaced with CCD.

The theoretical model for the system is similar to the model in TVI system. The received light still includes the direct transmitted and the scattered components. To avoid the backscattered light entering into the imager, the image tube is apart from the laser source. The UWLIS requires a huge power supply (10 kilowatts) to support the continuous wave laser. Its field of view is limited to 18° due to the mechanical structure.

The imager can directly generate a real-time standard television video. The results of in-water test demonstrate the operating of up to 4 attenuation lengths (AL) when running at real-time frame rates. The vision range can be improved to 6.3 AL when using 128-frame rates. In the similar condition, floodlight / silicon intensified target television camera configurations only produce a maximum imaging range of about 2.6 AL (Kulp, Garvis, & Kennedy, 1992).

(3) Modulated laser scanner

The laser scanning systems can greatly improve vision capability in dark seawater. The performances are limited in bright solar background, where the signal is mostly overlaid in the background noise. To solve the problem, the Naval Air Warfare Center developed an imaging system with optical modulation (Mullen et al., 1999).

The optical signal is modulated with a microwave sub-carrier superimposed on an optical carrier. It is transported through the scattering medium, and recovered by a high speed optical detector and a microwave receiver. The basic approach of the detection scheme is to make use of the way in which each component of the return signal is affected by the scattering of the modulated optical signal. Since the backscattered signal arises from reflections from a volume of randomly distributed scatterers, the modulation is essentially washed out in this signal component. The light which is reflected from an object retains the modulation. By filtering the return signal at the sub-carrier modulation frequency, this technique rejects the demodulated, scattered light while retaining the unscattered (or minimally scattered) modulated signal. This rejection of scattered light can also help to reduce the solar ambient noise.

In the experimental trial of a prototype, two 500W halogen lamps are used to simulate the high solar background in a 3.7m x 0.9m x 0.9m water tank. The receiver is an electro-optic identification sensor. To ensure that there is sufficient dynamic range to detect the high solar background levels and the modulated optical signal, the receiver is equipped with a PMT with a resistive voltage divider and a bi-alkali photocathode.

Figure 15. Modulate laser scanner in the Naval Air Warfare Center (1999)

High power is needed since the average optical power is reduced to 50% by modulating the transmitted beam. The output power of the laser is 1.5 W. The continuous wave output of laser was modulated in the frequencies of 10 MHz, 50 MHz, and 90 MHz. All modulation frequencies showed the capability of rejecting solar background noise, and the higher modulation frequencies helped to improve the target contrast. The 10 MHz modulation had no improvement in target contrast, while 90 MHz data improved the contrast clearly. Both the amplitude and phase information contained in a modulated optical signal provides a unique way of improving the performance of laser scanning by rejecting scattered light and enhancing target contrast.

(4) Structured light

The technique of structured light is widely used in the imaging fields. Its original purpose is to acquire the three-dimensional information of an object. When it is used in underwater 3D imaging, the technique shows an additional advantage in reducing the backscattering.

The structured light method involves the projection of a light pattern (circle, plane, grid, or more complex shapes) at a known angle onto an object (Hu, 1990). The most often used light pattern is generated by fanning out a light beam into a sheet-of-light. The illuminations usually are based on homogeneous light. Light patterns offer possibilities to simplify height measurement. To achieve the measurement as accurately as possible, a light stripe or other light pattern is projected with an angle on to the object. A camera monitors the scene from another angle. When the sheet-of-light intersects with an object, a bright line of light can be seen on the surface of the object. With some image processing and calculations, the observed distortions in the line can be translated into height variations. A full 3-dimensions

image can be constructed with scanning the scene (X-Y coordinates) and counting the height (Z coordinate) continuously.

A proper pattern in special environment can greatly simplify the process of triangulating the position of a point in space. In order to distinguish the stripes, the pattern can be coded with different grey levels or color spectrums. This allows the colored dots of light on a regular grid to be rapidly identified. The technique is even able to facilitate the location of wrinkles and other deformations on the human skin (Dubin et al., 1994).

(a) The scheme of the underwater laser-stripe scanning system

(b) A tubular target illuminated by the laser stripe

Figure 16. Laser stripe scan system in Cranfield University (1997)

The Offshore Technology Center in Cranfield University has developed a laser stripe scanning imaging system to build a 3D underwater scene (Tetlow & Allwood, 1995; Tetlow, Thomas, & Spours, 1996). Figure 16 shows the schematic configuration and an experiment image. The light source is a 100 milliwatts diode-pumped laser, which produces a continuous optical output in the green part of the spectrum (wavelength 532nm). The scanning unit uses two scanners, one to produce the stripe and the second to move this stripe over the work site. The frequency of the first is not critical but must be high enough that the

camera always perceives a solid stripe. The position of the second scanner is controlled by a demand signal from a computer so its position is always known. A conventional underwater TV camera monitors the stripe and captures images. Only one line is projected during any single TV frame or image. The 3D information can be extracted from each image using triangulation.

The configuration is able to construct a virtual 3D world (Tetlow & Spours, 1999). The scanning scheme makes only one stripe of light present in each image, so the backscattering is limited to the outgoing sheet of light from one stripe. As the result, the small illumination volume of laser stripe reduces optical scattering and improves vision range. The low power laser and TV camera make the system compact, low-cost, and suitable for small vehicles. They also bring disadvantages in processing the full view of the target. Because of the low power of laser and the slow scanning, the system cannot operate in real time. It typically takes 2 seconds in acquiring 50 frames for a complete composite image frame.

2.2.3 Interferometric projection

The previous section shows that the laser beam can be modulated in the temporal domain to reduce the scattering noise. The laser beam can also be modulated in spatial domain. The spatial interferometric projection is such a technique developed by the Harbor Branch Oceanographic Institution (Bailey, Blatt, & Caimi, 2003).

The approach relies upon the projected spatial gratings with subsequent detection against a coherent return signal for the purpose of noise reduction and image enhancement. The laser source is spatially modulated and projected into the water to illuminate the target. This method of illumination also allows a detector viewing at some angle to the target direction

to receive 3-dimensional signal information (Caimi, Bailey, & Blatt, 1999). It may use a continuous illumination source, and not require temporal synchronization between the reference and signal beams.

Figure 17. Equipment and geometry of the interferometric illumination (2002)

The scheme shown in Figure 17 utilizes an interferometric light source to illuminate the objects. The projected light is a spatially modulated interference pattern. The total apparent radiance at the detector is the sum of backscattered (B_{backsc}) and reflected ($B_{reflected}$) components.

$$B_{total} = B_{backsc} + B_{reflected} \quad (10)$$

The backscattering B_{backsc} includes the direct and diffuse components,

$$B_{backsc} = B_{backsc_direct} + B_{backsc_diffuse}$$

The backscattering B_{backsc} is the most primary noise in an illumination scheme. Referring to the geometry in Figure 17, its two components are determined by the equations (Bailey, 2002),

$$B_{backsc_direct} = 256 \int_{r_i}^{r_t} \frac{1 + \sin(2\pi fr \cos \alpha)}{2} \times \frac{e^{-cr \sin \alpha}}{(r \sin \alpha)^2} s e^{-cr} dr \quad (11)$$

$$B_{backsc_diffuse} = 256 \int_{r_i}^{r_t} 2.5k \frac{e^{-cr \sin \alpha}}{(4\pi r \sin \alpha)^2} s e^{-cr} dr \quad (12)$$

where B_{backsc_direct} is the direct component of backscattering;

$B_{backsc_diffuse}$ is the diffuse component of backscattering;

c is the attenuation constant at peak transmission wavelength;

k is the diffuse attenuation constant, $k=c/2.5$;

s is the average backscatter coefficient at detector to illuminator offset angle, and set to 0.018 for the model purpose;

r_t is the distance from detector to illuminated portion of the target along the path of integration, $r_t = \sqrt{z^2 + (d + y/p)^2}$;

r_i is the distance from detector to the first backscatter common volume element along the path of integration, $r_i = d/\cos \alpha$;

α is the angle between the path of integration and the target plan,

$$\alpha = \arctan\left(\frac{z}{d + y/p}\right).$$

The experiments used a 10-watt Argon ion laser and a Michaelson interferometer to verify the result. The primary idea of the interferometric illumination is that the scattered light is not structured. The interference is applied in the returned signal to discriminate against the non-structured scattered light. This method can achieve real-time image acquisition and

processing. It is also possible to predict the received signal and noise when giving the projected spatial frequency and water turbidity. Comparing with the point and single-line scanning methods, the interferometric method is a wide-area illumination, which definitely causes more scattering.

2.2.4 Range-gated system

In order to reduce the scattering noise, the above laser scanning method minimizes the illumination area of active light. Another different kind method is to minimize the illumination duration with pulsed light source. Range-gated system is such an application using pulsed illumination. It synchronizes the emission time of the laser pulse with the reception at the detector to eliminate scattered light.

Figure 18. Laser range-gated system concept

In the range-gated (also called time-gated) approach, a short laser pulse (typically of nanosecond duration) is projected, and the camera's shutter delayed by the time it takes for light to traverse from source to object, and back to camera (Swartz, 1994). The

scattering occurs in all spread path of light pulse. To eliminate scattered light, the shutter of camera (i.e., the gate in the Figure 18) is closed when the outgoing light pulse is traveling towards the object. It opens only when the return signal reaches the camera. In this way, the camera rejects the scattered light which follows a shorter or longer path, and only accepts the light directly reflected from the object (He & Seet, 2001). Due to the delay and open duration of shutter, the camera only captures a “slice” of view. The delay of shutter determines the distance from camera to the slice, and the open duration of shutter determines the depth of the slice.

The nanosecond duration of exposure is extremely short, so a range-gated system requires strong laser illumination (above 100 milli-joule per pulse), high voltage for Q-switching pulsed laser, and a sensitive receiver like intensified CCD camera or MCP intensifier. In addition, the electrical controls, such as time delay, electrical shutter, and laser pulse emission, require high stability and precision for the accurate synchronizations. With the development of electronics, range-gated systems are being popular in underwater visions, airborne visions, and atmospheric researches.

2.3 Image evaluation

A traditional imaging system just uses a large cross-sectional area beam and a simple camera arrangement. However, a scanning imaging system requires complex hardware setups and synchronization controls to get an image. Its goal is to obtain “good” images. Image quality index provides a judgment if it is worth to employ a complex scanning system to replace a traditional camera system.

Images are the carriers of visual information about the world. They are used as input to human visual perception. The primary task of perception is to measure and internally quantify attributes of items in the outside world with the aim to discriminate and identify these items. Image quality is usually described in terms of presence of visible distortions such as color shifts, edge distortions, blur, or fringing (Watson, Hu, & McGowan, 2001). It is the most crucial factor in most vision systems. Image quality index may be applied in many fields, such as image quality control, image algorithm benchmarking, and optimization of imaging systems (Lebart, Smith, Trucco, & Lane, 2003; Wang, Bovik, & Lu, 2002). An image acquisition system can use the quality metric to monitor and automatically adjust itself to obtain the best output. In a vision system design, the quality metric will help to select the best algorithm or to optimize the parameters in the system configuration.

Image quality assessment plays an important role in image applications. A great deal of effort has been made in recent years to develop subjective and objective quality evaluation. As image quality has different aspects in visual information, no one method can solely and fully characterize the image quality.

Three kinds of approaches have been widely used in imaging applications:

- (1) Subjective evaluation,
- (2) Objective evaluation based on pixel-to-pixel comparison,
- (3) Objective evaluation characterized by the Modulation Transfer Function (MTF).

2.3.1 Subjective evaluation

Subjective methods are popular in image assessments. These methods decide image quality based on human viewers' judgments. It usually acts as a necessary supplement of objective measurements.

Until now, only the subjective tests were standardized for image quality evaluation (Bernas, 2002). The documents describing assessment methods are published by International Telecommunication Union (ITU) in its standard file *Rec. ITU-R BT.500-10, Methodology for the Subjective Assessment of the Quality of Television Pictures* (ITU, 1995).

In subjective evaluations, images are presented and judged by a group of human viewers. In general, there are two classes of subjective assessments. First, there are assessments that establish the performance of systems under optimum conditions. These typically are called quality assessments. Second, there are assessments that establish the ability of systems to retain quality under non-optimum conditions that relate to transmission or emission. These typically are called impairment assessments.

For instance, two pictures are presented to the viewers. In quality assessments, one is an original image and the other is a processed image. In impairment assessments, the first is always the reference image, and the second is the processed image. The viewer evaluates image quality using a grading scale of five intervals (Excellent = 1, Good = 2, Fair = 3, Poor = 4, Bad = 5). Some researches also randomly decide the presentation order of the original and processed images.

The subjective test gives good results but its procedure is slow and expensive. The method requires human viewers during the whole procedures, so it is not suitable for most automatic systems.

2.3.2 Evaluation with pixel differences

The goal of an objective assessment is to supply quality metrics that can predict perceived image and video quality automatically. Recently a number of objective methods have been developed. The most widely used objective methods include mean square error (MSE), root mean square error (RMSE), signal-to-noise ratio (SNR), peak signal to noise ratio (PSNR), and mean absolute error (MAE) (Wang & Bovik, 2004). They calculate the pixel differences between a processed image and an original reference image. The image quality metrics in these methods are from the statistic of pixel-to-pixel differences.

Here is an example for PSNR computation (Power & Karim, 1998). The maximum amplitude of pixel is 255, and the minimum is 0. A pixel is at position (i, j) . In the reference image, its intensity value is written as $F(i, j)$, and in the processed image, the intensity value is $f(i, j)$. Assuming that the image contains N pixels, the PSNR index is scaled in dB:

$$PSNR = 20 \log_{10} \left(\frac{255N}{\sqrt{\sum [f(i, j) - F(i, j)]^2}} \right) \quad (13)$$

Figure 19 shows an example of PSNR calculation. High PSNR value means a processed image is close to its reference image. Image *a* has good appearance, and its PSNR is a high value of 18.2. PSNR in image *b* drops to 5.8 because of the contributions of noises.

Image c is a copy of the reference image, but it is shifted a few pixels to the right. Its PSNR value is very poor, only 1.2. The result implies that the pixel-to-pixel comparison is sensitive to position error.

Figure 19. Image quality evaluated with PSNR

PSNR and other pixel-difference based methods have low computational complexities. They are able to rapidly produce a unique numerical result. The whole computing is independent of viewing condition or human errors (Ruud, 2001). These methods are usually used to indicate the similarity between images. However, they do not concern image contents or perceived quality. They just pick up pixel differences between images. Accordingly they are very sensitive to pixel position errors. A small shift, rotation, or scale offset in images may cause great errors.

The next section will introduce an evaluation method which concerns image contents without the requirement of reference image.

2.3.3 MTF (Modulation Transfer Function)

As the demand for image quality, high resolution optical systems become more and more prevalent. MTF (Modulation Transfer Function) was originally used to evaluate quality of optical lenses. Now it becomes a mature method to analyze characteristics of hardware and images of optical systems.

(1) The conception of MTF

MTF is analogous to electrical frequency response. It describes the image structure as a function of its spatial frequencies, most commonly produced by Fourier transforming the image spatial distribution or spread function. Therefore, the MTF provides simple presentation of image structure information similar in form and interpretation to audio frequency response. The various frequency components can be isolated for specific evaluation (Patra, Mishra, Chandrakanth, & Ramachandran, 2002).

MTF is a precise measurement made in the frequency domain. The concept applied to audio signal is familiar. The higher is the frequency, the higher the pitch. The frequency of sound is measured in cycles per second, called Hertz. MTF is also a frequency response, except that it involves spatial frequency, cycles per millimeter instead of second, and distance instead of time. The cycle is line pairs with dark-line/white-space combination. The mathematics is exactly same. High spatial frequencies correspond to rapid changes in image density, i.e., fine image details.

MTF was initially applied to evaluate optical lenses which substantially decide output image quality. Resolution of optical hardware is customarily specified in line pairs per

millimeter (lp/mm). A line pair is one cycle of a light bar and dark bar of equal width and has a contrast of unity. Image contrast is mathematically defined as (Haykin, 2002):

$$MC = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad (14)$$

where $I_{\max}$ is the maximum intensity produced by an image (white) and $I_{\min}$ is the minimum intensity (black). Intensity is measured as W/m^2 (irradiance) by a detector.

MTF is a plot of contrast, measured in percent, against spatial frequency measured in lp/mm. This graph is usually normalized to a value of 1 at zero spatial frequency (all white or black). The MTF in a vision system is defined by the following equations. It actually is the summation of MTF of water medium, lens, and camera.

$$MTF = MTF_{\text{water}} \times MTF_{\text{lens}} \times MTF_{\text{camera}} \quad (15)$$

$$MTF(f) = \frac{M_{\text{final}}(f)}{M_{\text{original}}(f)} \quad (16)$$

where f is the frequency, line pairs per millimeter (lp/mm),

M_{final} is the contrast of the image captured by camera. It includes all factors affecting the MTF.

M_{original} is the contrast of the original USAF test pattern, and $M_{\text{original}} = 1$.

Optical components can be thought of as low pass filters, which allow low frequency signals to pass through and attenuate high frequency signals. MTF result describes the spatial frequency response with a line chart. An example is shown in Figure 20.

Figure 20. An example of MTF

A pattern of line pairs is used as an input image. The pixel values of the line pairs are a series of sine alterations. The frequencies of line pairs (i.e., sine functions) are gradually increased. When the pattern passes through an ideally perfect lens, the frequencies and amplitudes of output should be as same as the input. In a practical system, as shown in the figure, the signal is attenuated by a lens. The low frequency (frequency < 50 lp/mm) remains well, while the high frequency is severely degraded. The performance of the lens is described in the right chart. In low frequency zones, the modulated contrast of the output image has a perfect value, 100%. In high frequency zones, the contrast values drops down.

The right chart in Figure 20 is a MTF chart for a lens. The concept of MTF is also suitable for image quality assessment. An image includes two-dimensional information. Its pixel values can be extracted for image contrast calculation. The content in an image already includes many frequencies of information. For example, a sharp and detailed image portion means high frequency, and a large unchanged zone means low frequency. Accordingly, a MTF chart can be obtained from a single image.

(2) MTF acquisition

A MTF chart is a series of contrasts versus frequencies. It can be plotted by measuring image contrast. To get enough samples of contrast and frequency, special patterns should be used. The USAF 1951 resolution pattern is a standard pattern for contrast measurements. It contains a series of regular line pairs, whose sizes and separations indicate different frequencies. The layout of line pairs allows image contrast to be measured along both horizontal and vertical directions.

Figure 21. The USAF 1951 resolution pattern

The frequency, f , (line pairs / mm) of the USAF 1951 test pattern is defined as:

$$f = 2^{\left(\text{Group} + \frac{\text{Element} - 1}{6} \right)} \quad (17)$$

The definitions of group number and element number refer to Figure 21.

The USAF pattern includes a series of discrete frequencies from 0.25 lp/mm to 3.6 lp/mm. It has been widely used in underwater applications for both eye-observations and quantitative calculations.

Besides the direct contrast measurement, the Fourier transforms are also applied to calculate MTF. The Fourier transform is able to convert image pixels from spatial domain to frequency domain (Newbold, 2003). As shown in Figure 22, bar patterns are used as input signals, and its edges are blurred in practical output images. The Fourier transforms are applied to both input and output signals. The MTF is the normalized ratio between the Fourier transform of the input and output signals.

Figure 22. MTF calculation with Fourier transform

A straightforward method to find the MTF is the edge trace technique (Barakat, 1965). The detailed procedure is explained with a simple example in Figure 23. Bar patterns, such as the USAF 1951 pattern, are used as input. The average pixel value of each column is taken to form a one-dimensional data, which indicates the pixel changes at the edge. The edge data is called the Edge Spread Function (ESF), and the derivative of ESF is called the Line Spread Function (LSF) (Arney, Chauvin, Nauman, & Anderson, 2003).

A Fourier transform is applied to the LSF function. The result is a complex function in terms of frequency:

$$F(LSF(x)) = \text{Re}(\xi) + i \cdot \text{Im}(\xi)$$

The MTF is the ratio of each output value to each corresponding input value. It is calculated as the modulus of the result, and then normalized to the zero frequency value (Samei, Buhr, Granfors, Vandenbroucke, & Wang, 2005):

$$MTF(\xi) = \sqrt{[\text{Re}(\xi)]^2 + [\text{Im}(\xi)]^2}$$

The whole process of MTF calculation is summarized in the figure:

Figure 23. MTF calculation with edge trace and line spread function

2.4 Summary

This chapter introduces some typical laser imaging systems and image assessments for underwater imaging in recent years. Many kinds of laser, receivers, and mechanical configurations were studied and tested to deal with the scattering noise.

Image is a convolution of optical signal and noise. In order to improve vision range in turbid water environments, an essential solution is to reduce noises, i.e., the effect of scattering on images. Vision systems achieve this goal with different principles and mechanisms. Conventional imaging systems separate illumination source and receiver to avoid receiving the backscattered light. This is a simple way and gets very limited extension of vision range. Range-gated systems control the receiver aperture by time gating. They are able to eliminate intense backscatter originating from water, and allow the return from target to enter camera. Synchronous scanning systems operate by minimizing the common volume occupied by the laser illumination and the detector's field-of-view (Jaffe, 2005). The typical vision ranges of these systems are plotted in Figure 24 (Alan, 1992). Laser scanning system usually has the farthest vision range because the thin beam can transmit a long distance by concentrating its optical power.

Figure 24. Vision ranges of underwater imaging systems

A practical underwater vision system has to consider the power, size, weight of the components. The previous configurations require high-powered laser and very sensitive receivers. TVI was equipped with a 6 milliwatts laser and a PMT receiver. UWLIS used a 7 watts laser with 10 kilowatts power supply. Range-gate system needs high-power pulsed laser and ICCD cameras. The laser stripe scan system in Cranfield University used a small laser (only 100 milliwatts) and a normal CCD video camera. This lowers electrical power consumption but sacrifice scanning speed. The relative performances are summarized in a table below:

Table 2. Summary of the instruments for underwater vision

	Time varying intensity	Synchronous scanning system	Modulated laser scanner	Laser stripe scanning	Interfero- metric projection	Range gated system
Laser output	6 mw	7 w	1.5 w	100 mw	10 w	Pulse
Power supply for laser	watt	kw	kw	watt	kw	kw
Receiver	PMT	PMT	PMT	TV camera	Camera	MCP
Image output	real time	real time	real time	1 frame/s	real time	real time

These systems greatly extended the vision ranges in a laboratory setting. However, they are not suitable for small URV platforms, which have only limited capabilities of load and power supplies. Most laser scanning systems ignore the geometric size of lighting beam. An extremely thin beam is helpful to reduce scattering noise in the turbid water. It also makes scanning devices complicated, and requires more scanning cycles for the acquisition of full view of a scene.

The signal and scattering noise received by an imaging system depend on the illumination setting and the medium condition. This thesis proposes a scanning method with a variable illumination volume. The cross-sectional diameter of lighting beam is adjustable to accommodate to different water conditions. In turbid water, the illumination beam is concentrated to reduce scattering noise. The system promises good image, but needs long scanning cycles. The low update rate of image is acceptable as most small URVs move slowly. In clean water, the beam is expanded to speed up the scanning process without losing much image quality.

Image quality describes the presence of visible distortions of an image. The index helps to choose the best configuration or optimize settings in a vision system. Pixel-to-pixel comparison assessments, such as PSNR, count pixel differences between images. The methods are sensitive to the position error of pixels. MTF is able to evaluate a single image by analyzing image contents. It is able to provide high precision and comprehensive representation of imaging performance.

The system simultaneously considers water condition, illumination setting, and imaging quality. It requires only a low-powered laser and an off-the-shelf CCD camera. With the alterable beam setting, the system can effectively make use of laser in both turbid and clean water. The following chapters will discuss how the geometric size of laser beam affects the return signal and scattering noise, and then how to choose proper radius of laser beam in specified water medium.

Chapter 3 The Illumination Model

Illumination volume is the space that is filled by the light beam. The illumination volume of a parallel beam can be simply described with its cross-sectional radius. The amount of emitted photons is proportional to the illumination volume of light beam. Scattered flux is related to the illumination volume. To improve image quality, a laser scanning system uses a thin beam to illuminate the object. It reduces scattered noise by minimizing illumination volume. In underwater imaging systems, a proper setting of illumination volume helps to produce good image and effectively make uses of light power with optimization of size and speed.

Although illumination volume influences the returned signal and scattered noise, it was not quantitatively discussed in existing research works. Many researchers just used the thin laser beam in their scanning systems. This chapter will discuss a mathematical model to reveal how the illumination volume affects the distribution of signal and noise.

Illumination is a distribution of light energy in 3-dimensional space. When the light beam in a scanning system is moving, the flux distribution also changes with time. In our model, the flux distribution can be considered as constant when the scanning action is perfectly synchronized with the exposure of camera.

The surface of the object is assumed Lambertian. When a light beam is projected onto the object and reflected back, the light flux is classified into transmitted, forward-scattered,

and backscattered components, according to their behavior in light propagation. The total flux received by the camera is a linear superposition of these three components.

The basic principles, including Volume Scattering Function (VSF), Lambertian reflection, and Bidirectional Reflectance Distribution Function (BRDF), will be used to derive a new model. The parameter of illumination volume will be added into the calculations of the transmitted, forward-scattered, and backscattered components.

3.1 The related optical definitions

The basic optical definitions are clarified in the following table.

Table 3. Symbols and units of the optical variables

Variable	Symbol	Unit
Flux	P	W
Radiant exitance or irradiance (area distribution of flux)	E	W/m ²
Radiant intensity (solid angle distribution of flux)	I	W/sr

Flux is the rate of energy flow per unit time. It has the same units as power. It is the power which is leaving the target or the power which is collected by the detector.

The area distribution of flux is called radiant exitance (when the flux is leaving a surface) or irradiance (when the flux is falling onto a surface).

Radiant intensity is the solid angle distribution of flux. It is measured in terms of the power emitted per unit solid angle from an isotropic radiator. A theoretical point source radiates equally in all directions in 3D space.

Figure 25. Solid angle

Solid angle is numerically equal to the area divided by the square of the radius of the sphere.

Its standard unit is Steradian (sr). The solid angle of a full sphere is 4π .

$$\Omega = \frac{A}{r^2}$$

According to the geometrical relationship, the spherical area is

$$A = \pi(h^2 + n^2) = \pi \left[(r - r \cos \theta)^2 + (r \sin \theta)^2 \right] = 2\pi r^2 (1 - \cos \theta)$$

Then,

$$\Omega = A / r^2 = 2\pi(1 - \cos \theta)$$

3.2 Inverse Square Law

The Inverse Square Law describes that a source spreads its influence equally on surface of sphere. The intensity is inversely proportional to the square of the distance the light spreads.

Figure 26. Inverse Square Law

$$E = \frac{P}{A} = \frac{P}{\pi r^2}$$

where P is the power of the source,

E is the irradiance,

r is the distance that the irradiance spreads

3.3 Lambertian reflection

The reason that an object can be seen by human eyes (or cameras) is because the object emits light or reflects light, and that the light is detected by eyes (or cameras). Lambertian reflection, or diffuse reflection, is a common model to describe the light reflection from an object. Lambertian reflection is extensively cited in optical research because it approximates the characteristics of natural objects (Oren & Nayar, 1994). The Lambertian surface has a characteristic dull, matte appearance like chalk or dense opal glass. Most surfaces lie between perfect reflectors and perfect Lambertian surface.

Figure 27. Scattering of light governed by a cosine intensity relationship

In Lambertian reflection, when the incident light hits a surface, the reflected radiance is scattered uniformly in all directions. The brightness (radiance) of a Lambertian surface is constant regardless of the angle from which it is viewed. The intensity of the light

emanating in a given direction from any small surface component is proportional to the cosine of the angle of the normal to the surface.

The incident light is projected at an angle θ_i and reflected by a Lambertian surface. According to the definition of Lambertian cosine law, the intensity of diffuse reflection at angle θ_s is (Scott, 1988):

$$I_s = (\rho I_i \cos \theta_i) \cos \theta_s d\Omega dA \quad (18)$$

where I_s is the intensity of reflected light,

I_i is the intensity of incident light,

ρ is the diffuse reflection coefficient of the material,

θ_s is the angle from the normal to the reflected ray,

$d\Omega$ is the unit solid angle,

dA is the unit reflection area.

When an observer looks at the surface through an aperture of area dA_0 , the surface dA will subtend a solid angle $d\Omega_0$. The observer sees the intensity:

$$I_v = \frac{I_s}{(d\Omega_0 \cos \theta_s) dA_0} = \frac{(\rho I_i \cos \theta_i) \cos \theta_s d\Omega dA}{(d\Omega_0 \cos \theta_s) dA_0} = \frac{(\rho I_i \cos \theta_i) d\Omega dA}{d\Omega_0 dA_0} \quad (19)$$

where I_v is the intensity received by the observer,

$d\Omega_0$ is the solid angle that the surface dA subtends,

dA_0 is aperture area that the observer looks through.

The above equation shows that the reflected intensity is independent on view direction θ_s .

The observer sees the same intensity no matter at what angle he looks.

Lambertian reflection is a very simple model. The reflectance is also measured via a comprehensive model, the bidirectional reflectance distribution function (BRDF). In reflection (Figure 28), scatter from optical components can fill the entire sphere centered about the sample. The distribution of light within the sphere is a function of the incident angle, wavelength, and power, as well as parameters such as orientation, transmittance, reflectance, absorption, surface finish, index of refraction, bulk homogeneity, contamination, etc.

Figure 28. Definition of geometry for Bidirectional Reflectance Distribution Function

The BRDF is the angular distribution of outgoing radiation over the upper hemisphere relative to incoming radiation. It is defined in radiometric terms as the surface radiance divided by the incident surface irradiance. The scattered surface radiance is the light flux (P_s) scattered through solid angle (Ω_s) per unit illuminated surface area (dA) per unit projected solid angle ($d\Omega_s \cos \theta_s$). The surface irradiance is the light flux (P_i) incident on the surface per unit of illuminated surface (dA) (Stover, 1995).

$$BRDF \equiv \frac{\text{differential radiance}}{\text{differential irradiance}} \approx \frac{\frac{d^2 P_s}{d\Omega_s d(A \cos \theta_s)}}{\frac{dP_i}{dA}} \approx \frac{P_s / \Omega_s}{P_i \cos \theta_s} \quad (20)$$

The equation is appropriate for all angles of incidence and all angles of scatters. BRDF has units of inverse steradians (1/sr), and depending on the relative sizes of P_s and Ω_s , can take on either very large or very small values. For the entire specular reflection of a good mirror, P_s/P_i is close to 1, and BRDF is $1/\Omega_s$, which can be very large (Courreges-Lacoste, Schaarsberg, Sprik, & Delwart, 2003).

A perfect Lambertian reflector with reflection coefficient ρ_0 disperses the incident flux P_i uniformly through a solid angle of 2π steradians. The scattering angle θ_s ranges from 0 to $\pi/2$. The reflection coefficient is defined as the reflected power divided by the incident power:

$$\rho_0 = \frac{\int_0^{2\pi} \int_0^{\pi/2} (dP_s/d\Omega_s) \sin \theta_s d\theta_s d\Omega_s}{P_i} = \int_0^{2\pi} \int_0^{\pi/2} (BRDF \cos \theta_s) \sin \theta_s d\theta_s d\Omega_s = (BRDF)\pi$$

Then the BRDF of a Lambertian surface is defined as

$$BRDF = \frac{\rho_0}{\pi} \quad (21)$$

In Lambertian reflection, the reflectivity of surface is independent of direction so that only the total incident flux needs to be known. The Lambertian BRDF also shows the independence of the spatial distribution of the incident flux. A true Lambertian surface

under uniform illumination will have a fixed radiance regardless of its orientation. The lunar surface is nearly Lambertian, and for this reason it appears as a flat disk. There is no apparent shading at the edges that would give it the appearance of a sphere.

3.4 Bouguer's law (signal exponential attenuation with distance)

The attenuation effect has been introduced in Chapter 1. The attenuation of a beam of light by an optically homogeneous (transparent) medium is described by Bouguer's law. It was first stated by Pierre Bouguer in *Essay on the Gradation of Light* in 1729: "in a medium of uniform transparency the light remaining in a collimated beam is an exponential function of the length of the path in the medium". The effect was also independently discovered in various forms by Johann Heinrich Lambert in 1760 and August Beer in 1852. Beer's law discovered the relationship between the absorbance and concentration of an absorbing species. Beer's law can be regarded as an extension of Bouguer's law to solutions of fixed thickness but variable concentration of the absorbing solute.

The signal exponential attenuation with distance is also valid for turbid. Mathematically, Bouguer's law is written as

$$I = I_0 e^{-cL} \quad (22)$$

where I_0 is the incident intensity, I is the transmitted intensity, c is the attenuation coefficient of the medium, and L is the length of the path.

In Bouguer's law, the photons are treated as elastic pellets. The transmitted radiance I means that the photons maintain their initial trajectory directions in the propagation path. The absorbed photons disappear, and the scattered photons spread in the medium. The scattered intensity I_s may be received by a camera, and then make the total intensity in images higher than the value I that is expressed in Equation (22).

3.5 LIDAR Equation

A popular illumination model is the LIDAR (LIght Detection And Ranging) Equation. All laser-based underwater projects, including line scan and range-gated system, can be described by the first order LIDAR. The equation makes several simplifying assumptions. The output of light source is assumed to be fully contained within the field of view (FOV) of the collector, and the object has Lambertian diffusing surface. The two approximations are reasonable for many target and application scenarios. The first order LIDAR equation is (Leatham, 1991):

$$P_r = \frac{P_i e^{-2cL} \rho \cos \theta \left(\frac{H^2}{4} \right) \tau}{L^2}$$

Where P_r is the received flux,

P_i is the initial flux of illumination light,

c is the attenuation coefficient of the medium,

L is the distance from light source to target,

ρ is the target reflectivity,

H is the diameter of the receiver aperture,

τ is the optic efficiency of the receiver,

and θ is the angle from the illumination direction to the normal of the receiver.

The LIDAR equation is derived for the two concepts: Bouguer's law and the Inverse Square Law. Bouguer's law describes the exponential attenuation with distance in a dielectric medium. The Inverse Square Law describes the light intensity is inversely proportional to the square of the propagation distance. The LIDAR equation also considers the effects of the characteristics of the receiver and object, such as the receiver aperture, optical efficiency, and the reflectivity of the object.

The LIDAR equation is widely used in atmospheric and underwater researches, for example, to calculate the first order transmission, and to estimate the power budget in laser-based sensor design. However, it still has some obvious limitations. The chief problem is that it only considers the direct transmitted light, and it ignores the backward and forward-scattered light. In a turbid water medium, the effect of scattering is significant and can severely affect the accuracy of the model.

3.6 Volume Scattering

Chapter 1 describes the scattering by a single particle depends on the particle's shape, size, and material properties. Rayleigh and Mie models describe the scattering on a single particle. Rayleigh model describes that the scattered intensity distributes approximately equally in the forward and backward directions. It is applicable to small particles (diameter $< 0.1 \mu\text{m}$). Mie model describes that the scattered intensity concentrates in the forward direction if the particles size is big (diameter $> 1 \mu\text{m}$).

Volume Scattering Function (written in β , or VSF) defines the scattering for a medium volume (Maffione & Honey, 1992; Pereira, Ferreira, & Belsley, 2005). It characterizes the

scattering intensity as a function of angle when a light beam is incident on an infinitesimal volume (Petzold, 1972). At each angle from 0° (the original angle of the incident light) to 180° , the VSF is the ratio of the intensity of scattered light (in W/sr) to the incident irradiance (in W/m^2), per unit volume (in m^3). The unit of VSF is $\frac{\text{W/sr}}{(\text{W/m}^2) \cdot \text{m}^3} = \frac{1}{\text{sr} \cdot \text{m}}$, or $(\text{sr}^{-1} \text{m}^{-1})$.

Figure 29. Volume scattering

In Figure 29, a unit volume (dV) of scattering medium with suspended particles is illuminated with spectral irradiance, $E(\lambda)$. The scattered intensity in the direction θ is dI . The volume scattering function is defined as (Jerlov, 1968),

$$\beta(\theta) = \frac{dI(\theta)}{EdV} \quad (23)$$

where dI is the scattered intensity, (W/sr),

E is the incident irradiance, (W/m^2),

dV is a small volume, (m^3).

The scattering coefficient b is obtained by integrating $\beta(\theta)$ over all directions, i.e.,

$$b = \int_0^{4\pi} \beta(\theta) d\Omega. \text{ According to the geometry, } \Omega = 2\pi(1 - \cos\theta), \text{ and } d\Omega = 2\pi \sin\theta d\theta. \text{ The}$$

total scattering coefficient b can be divided into the forward (Ω from 0 to 2π , or θ from 0 to

$\pi/2$) component b_f , and the backward (Ω from 2π to 4π , or θ from $\pi/2$ to π) component b_b (Boss & Pegau, 2001).

$$b_f = \int_0^{2\pi} \beta(\theta) d\Omega = \int_0^{\pi/2} \beta(\theta) (2\pi \sin \theta) d\theta = 2\pi \int_0^{\pi/2} \beta(\theta) \sin \theta d\theta \quad (24)$$

$$b_b = \int_{2\pi}^{4\pi} \beta(\theta) d\Omega = 2\pi \int_{\pi/2}^{\pi} \beta(\theta) \sin \theta d\theta \quad (25)$$

$$b = b_f + b_b \quad (26)$$

The VSF varies in direction, and it also depends on the properties of water and particles. There are some instruments to measure VSF. Lisst-100 (Laser In-Situ Scattering and Transmissometry) from Westpark Technical Center is able to measure VSF at scattering angle from 0.097° to 19.5° (Gartner, Cheng, Wang, & Richter, 2001). The instrument AC-9 from WETLabs measures the absorption and scattering in all directions by using 9 discrete wavelengths (Levine et al., 1996).

3.7 The model with illumination volume

The basic optical characteristics, such as reflection, transmission, and scattering, have been individually explained in previous sections. In practice, these characteristics are mixed together during light propagation in a vision system (Mertens & Replogle, 1977). The following section will integrate them together to derive a full model. Besides these inherent effects, the geometric setting is also significant in a practical vision configuration, and will be considered in the model as well.

In the majority of underwater imaging systems, the camera and light source are placed on one vehicle. The common configuration is shown in Figure 30: the active light source is installed at one side, and the camera and optical instruments are at another side. In a rare configuration, the mother ship provides illumination, and the URV is equipped only with cameras.

Figure 30. Top view of active illumination of URV

In the following discussion, there is a presupposition that the photons are scattered only once; multiple scattering is not discussed here. When the deep sea is dark, and the ambient light is negligible, the light entering into camera can be classified into three components: direct transmitted light, forward-scattered light, and back scattered light.

According to the propagation path of the light, the flux is discussed in the two periods: from the light source to the object, and from the object to the camera.

- i. When light beam travels from the light source to the object, only backscattered rays may be captured by the camera. The backscattered rays are marked as (1) in Figure 30. They are noise because they do not contain any information of the object.

- ii. The direct transmitted ray (2) and forward scattered ray (3) travel ahead and reach the surface of the object. They have same effects in illuminating the object. After they are reflected by the object, and go towards the camera, the ray marked in (4) follows the original trace, and give the camera complete correct information of the object. The ray (5) is forward scattered. It carries information of the object, but it may fall onto inappropriate locations on the camera imager. It is considered as noise. The light (6) is backscattered, and will not enter the camera imager.

Finally the luminous flux received by the camera is the summation of the above components (1), (4), and (5). Among the various components, only (4) indicates the accurate details of the object, while (1) and (5) are noises.

Illumination volume has different effects in these components. The total flux increases proportionally with the illumination volume, while each component has different variability. Some researches reduce backscattering by minimizing the common volume, which is the intersection volume between the illumination beam and the field of view (Tetlow, Thomas, & Spours, 1996). This is one of the basic principles for laser scanning. The following section will highlight how these components are modified by the illumination volume.

A schematic light propagation and illumination volume are shown in Figure 31. A light beam (with continuous output) illuminates a Lambertian target in a turbid water medium. When a unit volume (dV) of light is traveling towards, it is scattered to all directions. The process is described by the Volume Scattering Function. The scattered light in the solid angle of Ω_{bs} will eventually fall onto camera imager. It does not carry any target information

to the final image, and it is called as backscattering noise. On the other hand, the unit light dV and its forward-scattered light spread to the target, and then are scattered by the target according to the Lambertian reflection. The light in the solid angle of Ω_s will fall onto camera imager. It is the desired return signal for imaging.

Figure 31. Light propagation

The processes of transmission, scattering, and reflection will be modeled with the Bouguer's law, volume scattering function, and the Lambertian reflection. First, the propagation with non-scattering will be considered. Then the effect of scattering will be added and to get a comprehensive illumination model.

3.7.1 Light transmission without scattering

The light that always remains its initial ballistic direction is called the direct transmitted light. If scattered rays are negligible in all light paths (i.e., although scattered rays exist, they will not reach a target or enter a camera imager), there are only the direct transmitted rays are considered in the illumination. The direct transmitted rays follow the Bouguer's law that

the intensity is exponentially attenuated by water molecules and suspending particles with distance. For a parallel light beam, the flux projected onto the object plane is determined by:

$$P_i = P_0 e^{-cL}$$

where P_i is the flux projected onto the object plane,

P_0 is the initial flux of the beam,

c is the attenuation coefficient of water and particles,

and L is the distance from light source to the target.

Lambertian reflection takes place at the target surface. The Bidirectional Reflectance

Distribution Function (BRDF) is defined as $BRDF = \frac{P_s / \Omega_s}{P_i \cos \theta_s}$. The reflection coefficient

of Lambertian is defined in Equation (16), which is $\rho_0 = (BRDF)\pi$. According to the

two equations, the total flux reflected by the target is

$$P_s = BRDF \cdot P_i \cos \theta_s \Omega_s = \frac{P_i \cos \theta_s \rho_0 \Omega_s}{\pi}$$

The radiant exitance of reflected light is $dE_s = \frac{dP_s}{A}$, and the illuminated area on the target

is $A = \pi R^2$,

$$dE_s = \frac{dP_s}{A} = d \left(\frac{P_i \cos \theta_s \rho_0 \Omega_s}{\pi} \right) / \pi R^2$$

Ω_s is a solid angle, and its corresponding planar angle in the cone is θ_s .

$\Omega_s = 2\pi(1 - \cos \theta_s)$, and $d\Omega = 2\pi \sin \theta d\theta$. The above equation is

$$dE_s = \frac{\rho_0 P_i \cos \theta_s d\Omega_s}{\pi R^2} = \frac{2\rho_0 P_i \cos \theta_s \sin \theta_s d\theta_s}{R^2} \quad (27)$$

where R is the cross-sectional radius of the parallel beam,

θ_s is the reflection angle,

and ρ_0 is the target reflectivity coefficient.

The total radiant exitance within solid angle Ω_s is $E_s = \int dE_s$, i.e.,

$$E_s = \int_0^\theta \frac{2\rho_0 P_i \cos \theta_s \sin \theta_s}{R^2} d\theta_s$$

E_s will be attenuated during distance L from the target to the camera in water medium, its magnitude becomes $E_s e^{-cL}$ when it reaches the camera imager. The flux falling on the camera imager is the integral of $E_s e^{-cL}$ in the whole beam whose cross-sectional area is $A = \pi r^2$, i.e.,

$$P_t = \int (E_s e^{-cL}) dA = \int_0^R (E_s e^{-cL}) 2\pi r dr = \int_0^R \int_0^\theta \frac{4r \rho_0 P_i e^{-cL} \cos \theta_s \sin \theta_s}{R^2} dr d\theta_s$$

The initial flux of the light source is P_0 . After traveling distance L , the light falls onto the target surface, and its flux is $P_i = P_0 e^{-cL}$. Substituting P_i into the above equation,

$$P_t = \int_0^R \int_0^\theta \frac{4r \rho_0 P_0 e^{-2cL} \cos \theta_s \sin \theta_s}{R^2} dr d\theta_s \quad (28)$$

According the geometrical relationship in Figure 31,

$$\cos \theta_s = \frac{L}{\sqrt{L^2 + r^2}}, \quad \sin \theta_s \approx \frac{H}{\sqrt{L^2 + r^2}}.$$

where L is the distance from the target to the camera,

θ_s is the reflection angle, (corresponding to the solid angle Ω_s)

and H is the radius of the pupil of camera.

The cross-sectional radius of the light beam R and the camera pupil H are usually much smaller than the distance L . The triangular equations are simplified as $\cos\theta_s \approx 1$, $\sin\theta_s \approx H/L$, $\theta_s \approx H/L$. Equation (28) is written as

$$P_t \approx \int_0^R \int_0^\theta \frac{4r\rho_0 P_0}{R^2} \frac{H}{L_b} e^{-2cL} dr d\theta_s \approx \frac{2\rho_0 H^2}{L^2} P_0 e^{-2cL} \quad (29)$$

Equation (29) is similar to the first order LIDAR equation, except that it does not involve the conversion efficiency of photon-to-electron.

The model does not calculate the scattered flux in the light propagation. It is only the direct transmitted flux. The parameter of illumination volume (i.e., the cross-sectional radius of light beam R), is not present in the equation. That indicates that the illumination volume does not affect the transmitted light signal. In atmospheric imaging applications or in clear water, the wide illuminations such as floodlights can be discretionarily used.

In a turbid water medium, the effect of scattering is significant, so a comprehensive model is necessary for accurate descriptions of lighting and imaging. The scattering phenomenon is defined by Volume Scattering Function (VSF). The following section will add VSF into the derivations of fluxes to reveal the effect of illumination volume in a scattering medium.

3.7.2 Light propagation with scattering

The phenomenon of scattering exists in the whole path length when light travels in water medium. It is called as forward scattering and backward scattering due to the direction of scattered light.

Due to the effect of forward scattering, some light rays may fall onto inappropriate positions on the object surface. They enlarge the illumination area. The backscattered rays return back before they reach targets, so they do not carry any information of objects. If the backscattered rays enter into the camera imager, they just bring plain white noise into the images.

Figure 32. Light propagation from light source to object

Figure 32 shows the scattering in the path of source-to-object. The initial flux is P_0 , and the radiant exitance is the area distribution of the flux, i.e., $E_0 = P_0 / (\pi R^2)$. At the distance l , the radiant exitance is E_l . According to the Bouguer's law, $E_l = E_0 e^{-cl}$.

The volume dV makes illumination light scattered in both forward and backward directions.

(1) Forward scattering in the path of source-to-object

According to the geometrical relationship between the solid angle Ω and the planar angle θ ,

$\Omega = 2\pi(1 - \cos \theta)$, and $d\Omega = 2\pi \sin \theta d\theta$. The forward scattering coefficient b_f is defined

as $b_f = \int_0^{2\pi} \beta(\theta) d\Omega = 2\pi \int_0^{\pi/2} \beta(\theta) \sin \theta d\theta$, where $\beta(\theta)$ is the volume scattering function.

Assuming that the forward-scattered flux uniformly distributes in all directions ($0 < \theta < \pi/2$), $\beta(\theta)$ is a constant, and the scattering coefficient b_f is

$$b_f = 2\pi \int_0^{\pi/2} \beta(\theta) \sin \theta d\theta = 2\pi\beta(\theta) \int_0^{\pi/2} \sin \theta d\theta = 2\pi\beta(\theta)$$

Then $\beta(\theta) = \beta(\theta_{fs}) = \frac{b_f}{2\pi}$.

According to the definition of volume scattering function in Equation (23), $\beta(\theta) = \frac{dI(\theta)}{EdV}$,

the radiant intensity of forward-scattered light by the unit volume, dV , is

$$dI_V = E_i \beta(\theta) dV = E_i \beta(\theta) (2\pi r dr dl)$$

where dI_V is the forward-scattered intensity (unit in W/sr) in dV .

The light in the solid angle $d\Omega_{fs}$ travels towards the target. Its intensity is attenuated by $e^{-c(L-l)}$ in the light path from V to the target T . When the light finally reaches the target, its intensity is

$$dI = dI_V e^{-c(L-l)} = E_i \beta(\theta_{fs}) (2\pi r dr dl) e^{-c(L-l)} = E_0 e^{-cL} \beta(\theta_{fs}) (2\pi r dr dl)$$

The scattered light in the solid angle of $d\Omega_{fs}$ will reach the target surface. Its incident angle is $\theta_i + \theta_{fs}$. In the whole illumination volume (radius R , length L), the total scattered flux,

which is forward scattered and projected onto the target plane, is the integration of dI in the light path L , the radius of beam R , and within the solid angle Ω_{fs} :

$$P_{fs_obj} = \int_0^L \int_0^R \int_0^{\Omega_{fs}} dI \cos(\theta_i + \theta_{fs}) d\Omega_{fs} = \int_0^L \int_0^R \int_0^{\theta_{fs}} E_0 e^{-cL} \beta(\theta_{fs}) \cos(\theta_i + \theta_{fs}) (2\pi r dr dl) 2\pi \sin \theta_{fs} d\theta_{fs}$$

$$\text{i.e., } P_{fs_obj} = 2\pi b_f E_0 e^{-cL} \int_0^L \int_0^R \int_0^{\theta_{fs}} r \sin \theta_{fs} \cos(\theta_i + \theta_{fs}) dr dl d\theta_{fs}$$

In Figure 32, when the distance L is much longer than the separation d , $L \gg d$, the angle θ_i

$$\text{is close to } 0. \quad \cos \theta_{fs} = \frac{L-l}{\sqrt{(L-l)^2 + r^2}}, \quad \sin \theta_{fs} = \frac{r}{\sqrt{(L-l)^2 + r^2}}, \quad \text{and } L-l \gg r.$$

Substituting the triangle relationships into the above equation,

$$\begin{aligned} P_{fs_obj} &\approx 2\pi b_f E_0 e^{-cL} \int_0^L \int_0^R \int_0^{\theta_{fs}} r \sin \theta_{fs} \cos \theta_{fs} d\theta_{fs} dr dl \\ &= 2\pi b_f E_0 e^{-cL} \int_0^L \int_0^R \frac{r}{4} (1 - \cos 2\theta_{fs}) dr dl \\ &= \frac{1}{2} \pi b_f E_0 e^{-cL} \int_0^L \int_0^R r (\sin^2 \theta_{fs} - \cos^2 \theta_{fs}) dr dl \\ &= 2\pi b_f E_0 e^{-cL} \int_0^L \int_0^R r \frac{(L-l)^2 - r^2}{(L-l)^2 + r^2} dr dl \\ &\approx 2\pi b_f E_0 e^{-cL} \int_0^L \int_0^R r dr dl \end{aligned}$$

i.e.,

$$P_{fs_obj} = \pi b_f R^2 L E_0 e^{-cL} \quad (30)$$

where P_{fs_obj} is forward scattered flux projected onto object plane, (W),

E_0 is the initial irradiance, (W/m²),

b_f is forward scattering coefficient, (m⁻¹),

L is the distance from light source to target, (m),

and R is the radius of the cross-sectional of light beam, (m).

(2) Direct transmitted flux in the path of source-to-object

The initial irradiance is E_0 , and the initial flux is $\pi R^2 E_0$. According to the Bouguer's law, after being attenuated with distance L , the direct transmitted flux projected onto the target surface is:

$$P_{t_obj} = \pi R^2 E_0 e^{-cL} \quad (31)$$

(3) Total flux projected onto the target

In the path from the light source to the target, the total flux projecting onto the target surface is the sum of the direct transmitted flux and the forward scattered flux:

$$P_{F_obj} = P_{t_obj} + P_{fs_obj} = (\pi R^2 + \pi R^2 L b_f) E_0 e^{-cL} \quad (32)$$

The effect of illumination volume is concerned below. The curves of Flux vs. Attenuation and Flux vs. Beam Size are shown in Figure 33. The parameters for the figures are set as:

$$E_0 = 10^5 \text{ W/m}^2, L_f = 0.6 \text{ m}, b_f = 0.5c$$

(a). Flux vs. attenuation

(b) Flux vs. beam size ($c = 1.8 \text{ m}^{-1}$)

Figure 33. The forward scattered flux in the path of light-to-object

In the figure of Flux vs. Attenuation, the direct transmitted flux P_{t_obj} is just exponentially attenuated with water attenuation c . The forward-scattered flux levels off when water attenuation coefficient $c > 2\text{m}^{-1}$. In a condition of extremely high scattering that the incident light flux is completely transformed to forward- and backward- scattered fluxes, the scattered fluxes are limited by the magnitude of the incident flux, and they will level off no matter how the water turbidity increases.

Irradiance is the area distribution of flux. When human eyes watch objects, the brightness is from the magnitude of irradiance. The illumination area of the beam is $A = \pi R^2$. The irradiance of the direct transmitted light is

$$E_{t_obj} = P_{t_obj} / A = E_0 e^{-cL}$$

For the forward-scattered light, the irradiance is

$$E_{fs_obj} = P_{fs_obj} / A = b_f L E_0 e^{-cL}$$

Both the direct transmitted irradiance and the forward-scattered irradiance are independent of the beam size. This means the illuminated area on the object has same. For example, a wider illumination beam has more flux ($Flux = Irradiance \times Area$), and it also covers more areas on the object.

Light rays (including the direct transmitted and the forward scattered rays) will be reflected by the target surface, and travels towards the camera. Lambertian reflection is considered in this process. Referring to Figure 30, when the light rays are leaving the target surface, they are classified into three parts:

- (1) Some rays maintain their ballistic trajectory, and eventually fall on the camera imager.

The flux falling on the camera imager is P_t .

- (2) Some rays are forward scattered in the path of object-to-camera. They will be received by the camera, and affected the image quality. The flux of these rays is P_{fs} .
- (3) Others are backward scattered. They will not be seen by the camera.

In the path of object-to-camera, the transmitted flux P_t and forward-scattered flux P_{fs} will enter the camera imager. The two values are calculated below.

(4) Transmitted flux in the path of object-to-camera

At the target plane, the incident flux is P_{F_obj} , and the illuminated area is πR^2 . Assuming the target surface is a Lambertian surface, and its reflectivity is ρ_0 , the radiant exitance from the target is:

$$E_{obj} = \frac{P_{F_obj}}{\pi R^2} \rho_0$$

Figure 34. Direct transmitted light in the path of object-to-camera

The calculation of direct transmitted flux is similar to the transmission with non-scattering.

According to BRDF equation, the radiant exitance within the unit solid angle, $d\Omega_s$, is:

$$dE_s = \frac{P_{F_obj}}{\pi R^2} \frac{\rho_0}{\pi} \cos \theta_s d\Omega_s$$

The light in the solid angle Ω_s will eventually fall onto the camera imager.

$$\Omega_s = 2\pi(1 - \cos \theta_s), \text{ and } d\Omega_s = 2\pi \sin \theta_s d\theta_s.$$

$$dE_s = \frac{2P_{F_obj}\rho_0}{\pi R^2} \cos \theta_s \sin \theta_s d\theta_s$$

The integration of dE_s in the angle Ω_s is:

$$E_s = \int dE_s = \int_0^{\theta_s} \frac{2P_{F_obj}\rho_0}{\pi R^2} \cos \theta_s \sin \theta_s d\theta_s$$

E_s is attenuated in the path from the target to the camera. When it falls onto the camera, it is:

$$E_t = E_s e^{-cL} = \int_0^{\theta_s} \frac{2P_{F_obj}\rho_0 e^{-cL}}{\pi R^2} \cos \theta_s \sin \theta_s d\theta_s$$

E_t comes from the area dA . $dA = 2\pi r dr$. The total flux is the integral of E_t over dA :

$$\begin{aligned} P_t &= \int E_t dA = \int_0^R E_t 2\pi r dr \\ &= \int_0^R \int_0^{\theta_s} \frac{4r\rho_0 P_{F_obj}}{R^2} e^{-cL} \cos \theta_s \sin \theta_s dr d\theta_s \\ &= \int_0^R \frac{r\rho_0 P_{F_obj} e^{-cL}}{R^2} (1 - \cos 2\theta_s) dr \end{aligned}$$

According to the geometrical relationships, $\cos \theta_s = \frac{\sqrt{L^2 - H^2}}{L}$, $\sin \theta_s = H/L$,

$\cos 2\theta_s = \cos^2 \theta_s - \sin^2 \theta_s$, The above integration equation is:

$$P_t = \int_0^R \frac{r\rho_0 P_{F_obj} e^{-cL}}{R^2} (1 - \cos^2 \theta_s + \sin^2 \theta_s) dr = \frac{2\rho_0 H^2}{L^2} P_{F_obj} e^{-cL}$$

P_{F_obj} includes the direct transmitted flux and the forward scattered flux. Its value is obtained in Equation (32). The direct transmitted flux received by the camera is:

$$P_t = \frac{2\rho_0 H^2 (\pi R^2 + \pi R^2 L b_f)}{L^2} E_0 e^{-2cL} \quad (33)$$

(5) Forward-scattered flux in the path of object-to-camera

The cross-sectional radius of the beam size is much smaller than the distance from the camera to the target, $R \ll L$. The illuminated area on the target is simplified as a point source with the irradiance:

$$E_s = \frac{\rho_0 P_{F_obj}}{\pi R^2}, \text{ where } \pi R^2 \text{ is the area illuminated by the light beam.}$$

Figure 35. Forward-scattered light in the path of object-to-camera

The total flux reflected by the target is $\rho_0 P_{F_obj}$. Referring to the figure, when a ray travels distance x to the poison dV , its energy is attenuated by the factor e^{-cx} and is inversely proportional to the square of the distance x . The irradiance is

$$E_{sl} = E_s \frac{e^{-cx}}{\pi x^2} = \frac{\rho_0 P_{F_obj} e^{-cx}}{\pi x^2}$$

The distribution of the forward-scattered flux is assumed uniform in all directions. The

volume scattering function is $\beta = \frac{b_f}{2\pi}$. The radiant intensity of forward-scattered light by

the unit volume dV is

$$dI_V = E_{sl} \beta dV = \frac{\rho_0 P_{F_obj} e^{-cx}}{\pi x^2} \frac{bf}{2\pi} (2\pi x^2 dx) = \frac{b_f \rho_0 P_{F_obj} e^{-cx}}{\pi} dx$$

The flux in the solid angle Ω_{fs} is $P_l = \int_0^{\Omega_{fs}} dI_V \cos \alpha d\Omega_{fs}$. When the flux travels towards and falls onto the camera imager, it is attenuated by the factor e^{-cy} . At the camera imager, the flux is

$$\begin{aligned} P_{fs} &= e^{-cy} P_l = e^{-cy} \int_0^{\Omega_{fs}} dI_V \cos \alpha d\Omega_{fs} \\ &= e^{-cy} \int_0^{\theta_{fs}} dI_V \cos \alpha (2\pi \sin \theta_{fs}) d\theta_{fs} \\ &= \int_0^{\theta_{fs}} \int 2b_f \rho_0 P_{F_obj} e^{-c(x+y)} \cos \alpha \sin \theta_{fs} dx d\theta_{fs} \\ &= \int 2b_f \rho_0 P_{F_obj} e^{-c(x+y)} \cos \alpha (1 - \cos \theta_{fs}) dx \end{aligned}$$

According to the geometrical relationship in the figure, $\alpha \approx \theta_s$, $dx \cos \alpha \approx dx \cos \theta_s = dl$,

$$x + y \approx L, \quad \cos \theta_{fs} \approx \frac{(L-l)}{\sqrt{(L-l)^2 + H^2}}, \text{ then}$$

$$P_{fs} \approx \int_0^L 2b_f \rho_0 P_{F_obj} e^{-cL} \left(1 - \frac{(L-l)}{\sqrt{(L-l)^2 + H^2}} \right) dl \approx \int_0^L 2b_f \rho_0 P_{F_obj} e^{-cL} \frac{H^2}{(L-l)^2} dl$$

i.e.,

$$P_{fs} \approx \frac{2b_f \rho_0 P_{F_obj} H^2 e^{-cL}}{L} = \frac{2b_f \rho_0 H^2 (\pi R^2 + \pi R^2 L b_f) E_0 e^{-2cL}}{L} \quad (34)$$

(6) Backscattered flux in the path of source-to-object

Like forward scattering, backscattering always takes place in all light paths. When illumination rays are traveling to objects, some rays are scattered back to the camera by the water medium. They would not reach the object. Some backscattered rays pass through the camera aperture and fall onto the camera imager. Some rays follow their trajectories, project to the object, and then are reflected by the object. When they are traveling from the object to the camera, backscattering takes place in the path of object-to-camera. However, in this stage, the backscattered rays go in opposite direction, and apart away the camera. They will not be seen by the camera.

Figure 36. The backscattering in the path of source-to-object

The calculation of backscattering is similar to the forward scattering. According to the definition of volume scattering function, at the angle θ , the radiant intensity of backscattered light by a unit volume, dV , is defined as:

$$dI_v = E_i \beta(\theta) dV = E_i \beta(\theta) (2\pi r dr dl), \text{ where } E_i = E_0 e^{-cl}$$

According to the geometrical relationship between the solid angle Ω and the planar angle θ , $\Omega = 2\pi(1 - \cos \theta)$, and $d\Omega = 2\pi \sin \theta d\theta$. The backscattering coefficient b_b is defined as

$$b_b = \int_{2\pi}^{4\pi} \beta(\theta) d\Omega. \text{ Assuming that the backscattered flux uniformly distributes in all forward}$$

directions, $\beta(\theta)$ is a constant, and the scattering coefficient b_b is

$$b_b = \int_{2\pi}^{4\pi} \beta(\theta) d\Omega = 2\pi \int_0^{\pi/2} \beta(\theta) \sin \theta d\theta = 2\pi \beta(\theta) \int_0^{\pi/2} \sin \theta d\theta = 2\pi \beta(\theta)$$

$$\text{Then } \beta(\theta) = \beta(\theta_{bs}) = \frac{b_b}{2\pi}.$$

The light in the solid angle $d\Omega_{bs}$ will enter the camera. Its intensity is attenuated by e^{-cl} in the light path from dV to the camera. When the light arrives at the camera imager, its intensity is $dI = dI_V e^{-cl} = E_l \beta(\theta_{fs}) dV e^{-cl} = E_0 e^{-2cl} \beta(\theta_{fs}) dV$.

Using the similar derivation in forward scattering, the flux that is backscattered and falls onto the camera image is:

$$\begin{aligned} P_{bs} &= \int_0^L \int_0^R \int_0^{\Omega_{bs}} dI \cos \alpha d\Omega_{bs} \\ &= \int_0^L \int_0^R \int_0^{\theta_{bs}} E_0 e^{-2cl} \cos \alpha \left[2\pi \sin \theta_{bs} \beta(\theta_{bs}) d\theta_{fs} \right] (2\pi r dr dl) \\ &= 2\pi b_b E_0 \int_0^{L_f} \int_0^R \int_0^{\theta_{bs}} (r e^{-2cl} \cos \alpha dr dl) \sin \theta_{bs} d\theta_{bs} \\ &= 2\pi b_b E_0 \int_0^{L_f} \int_0^R r e^{-2cl} (1 - \cos \theta_{bs}) \cos \alpha dr dl \end{aligned}$$

According to the geometrical relationship, D is the separation between the light source and

the camera, $x = \frac{L-l}{L}D$, $\cos \alpha \approx \frac{l+r}{\sqrt{x^2+l^2}}$, $\cos \theta_{bs} \approx \frac{\sqrt{D^2+l^2-H^2}}{\sqrt{x^2+l^2}}$. Substituting the

triangle relationships into the above equation,

$$\begin{aligned} P_{bs} &\approx 2\pi b_b E_0 \int_0^L \int_0^R \frac{H^2}{D^2 L^2} r^2 e^{-2cl} l dr dl \\ &= 2\pi b_b E_0 \frac{H^2}{D^2 L^2} \left[\frac{R^3}{3} \right] \int_0^L e^{-2cl} l dl \\ &= 2\pi b_b E_0 \frac{H^2}{D^2 L^2} \frac{R^3}{3} \frac{1}{4c^2} [1 - (1 + 2cL)e^{-2cL}] \end{aligned}$$

i.e.,

$$P_{bs} = \frac{\pi b_b H^2 R^3 E_0}{6D^2 L^2 c^2} [1 - (1 + 2cL)e^{-2cL}] \quad (35)$$

3.7.3 The effect of illumination volume

In the above calculations, the light components are individually analyzed in emission and reflection stages. The three components, direct transmitted flux, P_t , forward-scattered flux, P_{fs} , and backscattered flux, P_{bs} , will finally enter the camera imager to form an image. P_t carries the information of the object, P_{fs} carries the information but falls onto inappropriate locations in the image, and P_{bs} is only white noise. Their expressions are listed below:

$$\text{Direct transmitted flux: } P_t = \frac{2\rho_0 H^2 (\pi R^2 + \pi R^2 L b_f)}{L^2} E_0 e^{-2cL}$$

$$\text{Forward-scattered flux: } P_{fs} = \frac{2b_f \rho_0 H^2 (\pi R^2 + \pi R^2 L b_f)}{L} E_0 e^{-2cL}$$

$$\text{Backscattered flux: } P_{bs} = \frac{\pi b_b H^2 R^3 E_0}{6D^2 L^2 c^2} [1 - (1 + 2cL)e^{-2cL}]$$

The variables in the two fluxes are discussed below:

- (1) The radius of the camera aperture, H , affects all flux components. Aperture and shutter speed are two important settings in photography to decide the exposure of a photosensitive film or an electrical CCD chip. The opening of aperture is directly related to the amount of light falling onto the camera imager in unit duration. Although other components, such as optical lens set, also influence the received flux, they are not discussed here because they are fixed in a camera.
- (2) The object reflectivity, ρ_0 , affects the direct transmitted flux P_t and the forward-scattered flux P_{fs} . In light propagations, P_t and P_{fs} reach the object surface. They are affected by the object surface characteristics. In contrast, the backscattered light is reflected by the particles in water, and it never reaches the object surface.
- (3) The distribution of scattered flux is assumed uniform in all directions, so the effect of particle size is not considered in the model.
- (4) The backscattered flux is inversely proportional to the separation between the light source and the camera, D . In fact, indirect illumination has been used in practical applications (Wells, 1991). A wide separation helps to reduce the backscattered light. The maximum separation is limited by the size of an underwater platform.
- (5) The cross-sectional radius of the light beam, R , affects all flux components. The direct transmitted and the forward-scattered fluxes are proportional to R^2 , while the backscattered flux is proportional to R^3 . Therefore, the backscattered flux increases more rapidly than others when an illumination volume is being expanded.

Backscattered noise is the significant factor in light propagation when a wide illumination beam is used.

- (6) The distance L exists in the model for two reasons. First, According to Bouguer's law, all flux components exponentially degrade with the distance L . Secondly, the flux components also follow the Inverse Square Law, which means the spreaded fluxes are inversely proportional to the square of the propagation distance.

The flux components received by a camera imager are simulated in Figure 37. The figures are plotted in Flux vs. Attenuation. The beam size is set $R=0.03\text{m}$ (left figure), and $R=0.02\text{m}$ (right). The curves are based on the following settings:

$$L=0.6\text{m}, H=0.01\text{m}, \rho_0=0.8, D=0.05\text{m}, b_b=b_f=0.5c, E_0=10^5\text{ W/m}^2$$

(a). Beam size $R=0.03\text{m}$

(b) Beam size $R=0.02\text{m}$

Figure 37. The flux received by camera (Flux vs. Water Attenuation)

The curves show that the transmitted flux P_t is degraded with e^{-cl} and it drops very fast. The backscattered flux P_{bs} and the forward-scattered flux P_{fs} increase in the slightly turbid water ($c < 1.5\text{m}^{-1}$), and the levels off in highly turbid water ($c > 1.5\text{m}^{-1}$). Assuming a condition of extremely high scattering that the incident flux is completely transformed to

forward-scattered and backscattered fluxes, the scattered fluxes are limited by the magnitude of the initial flux, and they will level off no matter how the water turbidity increases.

Backscattered flux is noise because it has no information of the object. Forward-scattered flux carries the object information but it arrives to inappropriate locations in the camera imager. In slightly turbid water ($c < 1.5 \text{ m}^{-1}$), the forward-scattered flux P_{fs} is much lower than the transmitted flux P_t . In highly turbid water ($c > 1.5 \text{ m}^{-1}$), P_{fs} is much lower than the backscattered flux P_{bs} . Therefore P_{fs} is negligible to simplify the optical model, and P_{bs} is the most significant noise factor in turbid water.

Flux vs. Beam size is plotted in Figure 38. The backscattered flux increases rapidly with the beam expansion. In a wide-area illumination, backscattered flux exceeds the transmitted flux, and degrades the signal-to-noise ratio of image.

Figure 38. The flux received by camera (Flux vs. Beam size)

The signal-to-noise ratio (SNR) is:

$$SNR(dB) = 10 \log_{10} \frac{P_t}{P_{bs}} = 10 \log_{10} \frac{12\rho_0 (\pi + \pi L b_f) e^{-2cL}}{\pi b_\delta D^2 c^2 R [1 - (1 + 2cL) e^{-2cL}]}$$

The SNR is plotted in Figure 39. The SNR decreases when water turbidity increases. A thin light beam is able to get high SNR.

Figure 39. Signal-to-Noise Ratio in the received fluxes

Scattering is determined by water condition and illumination setup. In clean water, any sizes of illumination beams are able to produce high SNR. It is unnecessary to employ thin beam illumination. In turbid water, the narrow illumination volume shows great advantages in SNR improvement. It can effectively improve the performance of an imaging system.

3.8 Summary

Classical principles, such as the Lambertian reflection, Bouguer's law (i.e., signal exponential attenuation with distance), LIDAR equation, and volume scattering function, constitute the fundament of light propagation in a dielectric medium. They are widely used in many illumination applications. Underwater illumination is a complex interaction between photons and water medium. Existing models usually focus on a few particular parameters. For example, the TVI (Time Varying Intensity) system considers the

attenuation from water medium and the efficiency of photon-to-electron conversion. The existing models seldom discussed the illumination volume. In this chapter, a new model was built to analyze the effect of illumination volume in a parallel lighting beam. The model was based on the above fundamental models, and it provided comprehensive estimation of light flux.

The model assumes that the forward and backward scattered fluxes uniformly fill all directions in highly turbid water. The assumption is not valid in clear water environment where scattering presents obvious directionality. In highly turbid water, the directionality of scattering disappears, and the model is able to represent the transmission and scattering of a parallel light beam.

In this model, light propagation is divided into two stages: from light source to object, and from object to camera. In each stage, light flux is regarded as a linear superposition of transmitted, forward-scattered, and backscattered components. Multiple scattering is dominating in highly turbid water. The model scattered flux through the light propagation path. All components are computed with the volume scattering function and Bouguer's law by considering the size of light beam and the geometric layout of hardware.

The results reveal the effect of illumination volume in the distribution of light signal and noise. In slightly turbid water (water attenuation $c < 1.5\text{m}^{-1}$), forward-scattered flux is much lower than the transmitted flux. In highly turbid water ($c > 1.5\text{m}^{-1}$), forward-scattered flux is much lower than backscattered flux. Forward-scattering is negligible in camera imaging. Backscattering has high magnitude and it is the significant noise in images. When water turbidity increases, the direct transmitted flux degrades quickly, while the backscattered flux increases and levels off. When the illumination volume is expanded, the

backscattered noise increases faster than the transmitted signal. This downgrades the signal-to-noise ratio.

The theoretical result quantitatively explains that an extreme thin laser beam in a scanning system is capable of reducing backscattered noise. It also shows that the separation between the light source and the camera is helpful to reduce the reception of backscattered noise. The model can be used in practical applications to optimize light source settings, and to predict the signal-to-noise ratio in output images.

The curves of Flux vs. Water Attenuation and Flux vs. Beam size show the effect of illumination volume. The results will be verified in the next chapter with experimental measurements.

Chapter 4 Experimental Setup and Results

This chapter will verify the illumination model described in the previous chapter. Although light flux is assumed to be comprised of transmitted, forward-scattered, and backscattered components in the theoretical model, it presents as a whole in practice. These flux components are unable to be distinguished and individually measured. For example, the flux projected onto target includes transmitted and forward-scattered components, and the flux received by camera includes transmitted and backscattered components.

An indirect measurement is applied in this chapter. When a normal target is installed, the flux received by camera is the sum of transmitted component and backscattered component. When the target is replaced by a light trap, all the transmitted light is absorbed, then the flux received by camera is only the backscattered component. The transmitted light is obtained by calculating the difference of the two measurements. The flux projected onto target includes is the sum of transmitted and forward scattered components. It will be measured and compared with the theoretical value.

A CCD camera is used to measure the illumination flux. Its video output is grabbed and displayed on a computer screen. The camera system outputs image pixel values (i.e. brightness), while the theoretical model uses a different metrical unit, flux. Image pixel values produced by CCD depend on the accumulation of photons. They are linear proportional to the exposure duration. Accordingly, image pixel values can be transformed to flux by using time normalization.

In the theoretical model, light flux is affected by both illumination volumes and water conditions. A turbid water environment is simulated in a 0.6 meter long water tank. An expanded green laser beam acts as a light source. To get experimental curves of Flux vs. Water Attenuation, the water turbidity is adjusted by mixing a milky liquid, Mylanta antacid. The water attenuation coefficient is accurately monitored by an attenuation meter, the AC-9. The distance between camera and target is always fixed at 0.6 meter, i.e., the length of water tank.

4.1 Experimental setup and methodology

The experimental setup is shown in Figure 40. It includes a laser source, beam control lens, a 0.6 meter long water tank.

Figure 40. Experimental configuration

Since the effect of illumination volume is emphasized, the laser beam should be precisely adjusted. The intensity of output beam is adjusted by a density filters, and then expanded

by a spatial filter and a convex lens. Its illumination volume (i.e., cross-sectional diameter of beam) is tailored by an iris.

The schematic drawing in Figure 41 clarifies the hardware configuration and geometrical layout. The main variables in the theoretical model, such as the cross-sectional radius of the light beam (R), the water attenuation coefficient (c), the distance from the light source to the object (L), and the separation between the light source and the camera (D), are labeled out in the figure. The setup is designed to measure light fluxes in various illumination volumes and in various water conditions. The target and light trap are used for normal imaging and the measurement of backscattering respectively. The beam radius, R , and the water attenuation coefficient, c , are adjustable in measurements. The other variables, such as the camera settings are fixed.

Figure 41. Experiment scheme

All instruments are outside the water tank. To avoid reflection from the walls of the tank, black cloth is placed inside the tank and covers the side walls. The illumination beam is not perpendicular to the front wall. This avoids the multiple reflections between the front and back walls.

The flux of light is received and converted to images by a monochromatic CCD camera. To avoid the ambient illumination, a band pass filter is installed in front of the camera. This ensures that only the light in 532nm wavelength can pass through the filter and be received by the camera. In the scheme, there are two camera positions and three kinds of target. Three kinds of fluxes will be measured:

- (1) When the camera is installed at position 1, and a ground glass is installed, the flux projected onto the target will be measured. This configuration simulates the scene when light is being projected to the target. The ground glass target acts as an image plane. It is similar to the screen in a cinema. The camera looks at the plane and measures the optical projected on the plane. Camera images are the results of two flux components: the direct transmitted component and the forward-scattered component. According to Equation (32), the flux projected onto the target is theoretically defined as:

$$P_{F_obj} = P_{t_obj} + P_{fs_obj} = (\pi R^2 + \pi R^2 L b_f) E_0 e^{-cL}$$

- (2) When the target is replaced with a light trap, no light will be reflected by the target. The camera placed at position 2 will only collect the backscattered flux, which is reflected back by suspending particles in the path from the light source to the target. The received backscattered flux is theoretically defined in Equation (35):

$$P_{bs} = \frac{\pi b_b H^2 R^3 E_0}{6 D^2 L^2 c^2} [1 - (1 + 2cL) e^{-2cL}]$$

- (3) When a normal Lambertian target is installed, the setup is a common illumination scene. The camera placed at position 2 will collect both transmitted and backscattered fluxes. In the theoretical model, the total received flux is:

$$P = P_t + P_{bs}$$

$$P_t, \text{ is the transmitted flux, } P_t = \frac{2\rho_0 H^2 (\pi R^2 + \pi R^2 L b_f)}{L^2} E_0 e^{-2cL}.$$

The three configurations will be adopted in the following measurements. Although we are unable to distinguish or directly measure the transmitted flux, P_t , the three measurable fluxes, P_{F_obj} , P_{bs} , and P , can provide enough verifications for the theoretical model.

In order to verify the effect of illumination volume, three beam settings are applied. The cross-sectional radius of beam, R , is set as 0.01m, 0.02m, and 0.03m, respectively. In each beam setting, camera measurements are taken when water attenuation coefficient, c , gradually increases from 0.1 m^{-1} (i.e., clean water) to 4.0 m^{-1} (turbid water).

Before starting measurement, the three important elements, the light source, water medium, and camera, will be discussed. Their configurations directly affect the precision of measurement.

4.1.1 Light source

The light source in the experiment is a diode-pumped laser from CrystaLaser Inc. It outputs green light of 532nm wavelength. Among visible spectrums (wavelengths from about 400nm to 700nm), green light is usually preferred as it has low absorption and good transmission capability in water. The continuous wave power of the laser is as high as

50mw. The bright light may produce an eye hazard if viewed directly. It is also too bright for the CCD camera. The output beam is attenuated by a density filter set whose optical density is 1. Accordingly only 10% output power, i.e., 5mw, is used for the illumination in experiments.

The output of a laser consists of main beam and noise. The noise is from the intrinsic mechanism of laser. For example, the material in laser cavity is heated by light due to the photo-thermal effect, and its volume expands and its density decrease upon heating. As the refractive index of materials is proportional to the density, the refractive index of the heated part is smaller than other parts. The material acts as a concave lens and causes light divergence. This is called thermal lens effect (Abramczyk, 2005).

In the experiment, the laser output energy is strong and exceeds the detection range of the camera. It has to be degraded by a density filter set which is composed of four filters (OD = 0.1, 0.2, 0.2, 0.5, and the total OD is 1). The surfaces of these filters cause multiple reflection of the laser light, and degrade the beam quality.

(1) Scheme of beam expander

(2) Spatial filter

Figure 42. Beam expander and spatial filter

A spatial filter is able to remove noise in the laser output beam. It is composed of a microscope objective lens and a pinhole. The microscope objective lens focuses the laser beam precisely at the location of the pinhole. Since the off-axis light (noise) will not be

focused at exactly the same point in space as the on-axis beam, it will be blocked by the pinhole.

The parameter of the microscope objective lens and the pinhole are recommended by the following expression (Newport Product Datasheet):

$$p = \frac{2.4\lambda f}{d}$$

where p is the pinhole diameter,

λ is the wavelength of laser beam,

f is the focal length of the microscope objective lens,

d is the diameter of laser beam.

In the experiment, the parameters are chosen: laser beam $d = 0.36\text{mm}$ (CrystaLaser Data Sheet); the microscope objective lens $f = 2\text{mm}$, magnification 60X; the pinhole $p = 10\mu\text{m}$.

The output of the spatial filter is collimated by a convex lens. The beam is expanded to 0.04m (cross-sectional radius), and it is tailored by an iris to three settings: $R = 0.01\text{m}$, 0.02m, and 0.03m.

4.1.2 Water condition monitoring and simulation

The energy of light is exponentially degraded by water turbidity, so the water attenuation is a crucial factor in the theoretical model and practical measurement. There are three parameters for water description: absorption coefficient, a , scattering coefficient, b , and attenuation coefficients, c . They are related by the correlation of $c = a + b$. During the experiment, a and c can be accurately measured with WETLabs Absorption Attenuation Meter, AC-9. b is solvable from a and c .

Figure 43. Optical path configuration for attenuation beam (c)

Figure 44. Optical path configuration for absorption beam (a)

The AC-9 can perform concurrent measurements of the attenuation and absorption characteristics of the water by incorporating a dual path optical configuration in a single instrument. Each path contains its own source, optics, and detectors appropriate to the given measurement. The two paths share common filter wheel, control and acquisition electronics. The optical path of the beam (c) performing attenuation measurement is shown in Figure 43, and the beam (a) performing absorption measurement is shown in Figure 44.

In the configurations, light from a DC (direct current) incandescent source passes through a 1mm aperture. The light is then collimated with a 38mm lens followed by a 6mm aperture.

The collimated light passes through band pass filters mounted upon a continuously rotating filter wheel, creating a narrow band spectral output. The filter wheel holds nine 12.5mm diameter, 10 nm full width half maximum (FWHM) filters that are spaced around the perimeter at approximately a 3:1 ratio with associated blank spaces. This configuration provides a chopped output for the detectors, which compensates for temperature coefficients in the detector and amplifier circuitry as well as providing low level ambient light rejection. Once the light has passed through the filter wheel, the beam passes through a beam splitter, creating a primary beam and a reflected beam. The intensity of the reflected beam is measured by a reference detector. Its value is used to compensate the drift of lamp output. The primary beam then passes through a pressure window into the sample water volume.

A flow tube encloses the water path. Once through the water path, the light passes through another pressure window and then comes into a receiver detector. The AC-9 is able to ensure the same optical losses for the reference beam and receiver detector.

Comparing Figure 43 with Figure 44, *c*-beam and *a*-beam optics are similar. The *c*-beam uses a blackened flow tube, so scattered light is absorbed and it does not contribute to the measurement of transmitted intensity. The *a*-beam uses a reflective tube to reflect scattered light back into water volume. This ensures that it measures absorption coefficient only.

The typical turbidity of Singapore coastline seawater is about 1.5 m^{-1} in field survey (He & Seet, 2004). In the experiment, water turbidity is simulated by Mylanta antacid, which has been shown to be a good match to the volume scattering function of natural water (Duntley, 1971). Mylanta antacid is a dense liquid appearing like milk. It mainly contains aluminum hydroxide (AlOH) and magnesium hydroxide (MgOH). Its particle size is about

5.0 μm , and it can suspend in water for a long time. They are able to keep the water turbidity status for more than one hour.

Figure 45. Water attenuation produced by Mylanta antacid

Mylanta antacid is widely used in many underwater projects because its optical properties are close to that of turbid seawater. The correlation between Mylanta concentration and the beam attenuation coefficient is derived from the AC-9 measurement. The experimental measurement shows that the values of c and a are linearly proportional to the volume of Mylanta antacid. According to the measurement, every 0.1 milliliters Mylanta in 60 liters of water causes the increments of 0.23 m^{-1} in c and 0.03 m^{-1} in a for the 532nm light.

4.1.3 CCD camera

A monochromatic CCD camera, PULNIX TM-6300, is used to measure the optical signals. It has a high sensitivity and low noise output (signal to noise ratio $> 50\text{db}$). The active pixel array on the CCD is 648×484 . According to the principle of CCD chip, the output image is a result of flux accumulation during exposure. In the setup, the exposure of

camera is accurately triggered by an external delay generator, DG535, whose time resolution is as high as 5 picoseconds. The aperture of camera can be adjusted by an imaging lens in front of the CCD chip. The maximum aperture is set for all image captures.

The CCD camera is used as a flux meter. Its image output is normalized by exposure time and then transformed to flux. To lower the measuring errors, the camera should avoid the effect of dark current and light interference.

(1) Exposure and dark current

Dark current is one of inherent characteristics of CCD. The effect is caused by the thermal motion of atoms, and finally it introduces noises to images. Dark current may make hot spots appear in images although the aperture of camera is completely closed. The magnitude of dark current is high in long exposure (> 1 sec). In a normal photo shoot, the exposure time is usually less than 50ms, and the noise caused by dark current is much smaller than the illumination signals.

The left curve in Figure 46 shows the experimental measurement of dark current noise. The camera is triggered with its aperture completely covered. The output (i.e., image brightness or pixel value) of the camera keeps 15.5 when the exposure time is less than 20ms, and it disorders when the exposure time is great than 20ms. In the following experiments, the camera exposure is set less than 10 ms. The noise from dark current is considered as a constant. And it has same magnitude in all images.

(1) Dark current noise vs. exposure

(2) Camera output vs. light irradiance

Figure 46. Camera dark current and response**(2) Response to irradiance**

The photon-to-electron conversion is linear when CCD works in a proper illumination condition. The output of CCD camera is usually digitized from 0 to 255 by a frame grabber. Strong light may cause CCD saturation. The right curve in Figure 46 shows the image brightness response to illumination light. In the measurement, the light beam directly projects to the camera, and its irradiance is adjusted by a density filter set with optical density from 0 to 1, i.e., $OD = 0$ (i.e., filter not installed), 0.1, 0.2, ..., 0.9, 1. The exposure time is 1ms. The figure shows that the CCD camera has a linear response to the illumination light.

(3) Aperture and interference speckle

Besides exposure time, aperture also affects image appearance and quality. Aperture determines the amount of light entering the camera in a unit time.

Laser is a coherent light source, which can lead to the appearance of the phenomenon of speckle. When a scattering surface is illuminated by coherent light, the grainy speckles

arise at the surface. This is due to the interference that occurs between the light rays as they are scattered by different points on the surface (Rastogi, 1997). The speckle intensity variations are detected via a finite detector aperture so that the measured intensity is smoothed by means of the spatial integration. Speckle reduction is implemented by increasing the aperture of the detector (Iwai & Asakura, 1996). Two experimental images are compared in Figure 47. The effects of speckle and interference are very obvious in the left image, where a small aperture is used in the camera system.

Figure 47. Speckle and interference in camera images

To avoid the interference speckles, the aperture of the camera is always set to the maximum opening in the following experiment. The large aperture shortens camera exposure and then restrains the occurrence of black current. It also reduces the depth of field. As the distance between the target and the camera is fixed in the experiment, the depth of field does affect the image comparison.

(4) Images normalization with exposure time

The theoretical model uses the term *flux* for the power of the optical signal, and *irradiance* for the area distribution of flux. Digital images use *pixel values* to present the brightness.

When a CCD chip is exposed under optical lights, the flux falling on each CCD cell is transformed to an electrical voltage and then to an image pixel value. Since the transforms from photons to image pixels are linear, pixel values can be used to indicate and calculate the flux of illumination light.

CCD has limited capability to collect the electrons which are converted from photons. Strong illumination may make CCD saturation, i.e., the brightness ceiling of an image is 255. In the experiment, the illumination intensity has a wide range because it is exponentially attenuated by the turbid water. A CCD camera is able to adjust exposure time to avoid too bright (over exposure) or too dark (underexposure) appearance in image. For example, a camera needs long exposure time when the illumination light is very low.

Exposure time is the opening duration of the camera shutter. Photons are accumulated on a CCD chip when the shutter is open. So the amount of the photons is directly related to the exposure time. The photons are converted to electrical current, which is digitized by a framer grabber to form image pixels. The exposure time of the camera determines the image brightness. An experimental measurement (Figure 48) shows that the image response to exposure time is linear.

Figure 48. Image brightness response to exposure time

Figure 49 shows the conversion process from light flux to image. According to the characteristics of CCD camera, the conversions from photons to electrical currents and from currents to image pixel brightness are linear functions. A parameter k is used to represent the total conversion efficiency. The entire conversion is

$$\text{Brightness(i.e., PixelValue)} = k \cdot \Delta t \cdot \text{Irradiance} = \frac{k \cdot \Delta t \cdot \text{Flux}}{\text{Area}}$$

where Δt is exposure time, and the parameter,

k is the conversion efficiency from photon to image brightness,

Irradiance and Flux are for the incident illumination,

Area is the illuminated area on the target.

Figure 49. Conversion from flux to image pixel value

(5) Comparison method

The theoretical model in the previous chapter describes flux or irradiance, while the experimental measurement of camera images gets brightness (i.e., pixel value). In order to use images to verify the model, the image pixel values are converted to irradiance by dividing the exposure Δt and the photo-electron-brightness conversion coefficient k .

Irradiance is defined as area distribution of flux. The theoretical irradiance projected on the target is

$$E_{theory_obj} = \frac{P_{t_obj} + P_{fs_obj}}{\pi R^2} = (1 + Lb_f) E_0 e^{-cL} \quad (36)$$

where P_{t_obj} is the direct transmitted flux component,

P_{fs_obj} is the forward scattered flux component,

and R is the cross-sectional radius of the light beam.

The theoretical backscattered irradiance received by the camera is

$$E_{theory_bs} = \frac{P_{bs}}{\pi H^2} = \frac{b_b R^3 E_0}{6D^2 L^2 c^2} [1 - (1 + 2cL) e^{-2cL}] \quad (37)$$

where P_{bs} is the flux which is backscattered and received by camera pupil,

and H is the cross-sectional radius of the illumination light.

The total irradiance received by the camera is

$$E_{theory_camera} = \frac{P_t + P_{bs}}{\pi H^2} = \frac{2\rho_0 (R^2 + R^2 Lb_f)}{L^2} E_0 e^{-2cL} + \frac{b_b R^3 E_0}{6D^2 L^2 c^2} [1 - (1 + 2cL) e^{-2cL}] \quad (38)$$

where P_t is the direct transmitted flux,

P_{bs} is the flux which is backscattered and received by camera pupil,

and H is the cross-sectional radius of the illumination light.

In an image, the experimental measurement of irradiance is

$$E_{measure} = \frac{1}{MN} \sum_{x=1}^M \sum_{y=1}^N \frac{Pixel(x, y)}{k \Delta t} \quad (39)$$

where $Pixel(x, y)$ is pixel brightness at location (x, y) ,

M, N are the length and width of the image,

Δt is the exposure duration. It is measured from the camera.

k is an efficiency constant of photoelectric transform.

4.2 Experimental results

Although the direct-transmitted, forward-scattered and backscattered components are calculated individually in the theoretical model, they are mixed together in practical illuminations. These components are unable to be distinguished or individually measured. Alternatively, three fluxes will be measured to verify the theoretical components:

- (1) The flux projected onto the target is the sum of the forward scattered component and the transmitted component. It is measured by the camera 1 (Figure 41).
- (2) When a Lambertian target is installed, the flux collected by camera 2 (Figure 41) is the sum of the backscattered component and the transmitted component.
- (3) When the reflective target is replaced by a light trap, the flux collected by camera 2 is only the backscattered component.

4.2.2 The irradiance projected onto the target

In last section, the total flux projected to a target is theoretically calculated:

$$E_{theory_obj} = \frac{P_{t_obj} + P_{fs_obj}}{\pi R^2} = (1 + Lb_f) E_0 e^{-cL}$$

It shows that the irradiance projected onto the target is independent of beam size (i.e., the parameter R). The irradiance is just exponentially attenuated with the light path, L , and the water turbidity c .

Referring to the scheme in Figure 41, a ground glass target is used to receive the flux. It acts as the screen in a cinema. The irradiance is measured with camera 1. The hardware configuration is simplified in Figure 50.

Figure 50. The measurement of forward projected flux

After the expanded laser beam is collimated by a convex lens, it passes through a glass, which is plated with an USAF (United States Air Force) 1951 test pattern. The illumination beam is filtered by the USAF bar pattern and then projected into the water. Finally the beam falls on the ground glass and its illumination pattern is recorded by a CCD camera.

For the measurement of projected flux or irradiance, the light beam may directly project onto the image plane, without the USAF filter. And the image output of the camera is plain grey. The installation of the USAF filter provides more information in images than plain grey. For example, the grey part of images is used to measure the irradiance which passes through the transparent part of USAF, and the black line pairs in the image means no light (the light is blocked by the black part of USAF). The line pairs help human eyes to intuitively observe images.

The cross-sectional radius of the laser beam, R , is adjustable. It is set to 0.01m, 0.02m, and 0.03m, respectively. At each radius setting, the water attenuation coefficient, c , is gradually increased from 0.1 m^{-1} to 4.0 m^{-1} by adding Mylanta antacid. The illumination intensity degrades fast in turbid water. To avoid overexposure or underexposure, the exposure time of camera is adjusted by a delay generator DG535 for every individual

image. The exposure time is set to make most of pixel values in the range of 50 - 200. (The possible pixel value is from 0 to 255. 0 stands for complete black, and 255 for complete white.) This exposure setting gives the output images good appearances with proper brightness and contrast.

Figure 51. Images in the measurement of projected irradiance

Some typical experimental images are listed in Figure 51. They have similar appearances but they are taken in different water conditions and with different exposure durations. The images (a) (b) (c) in the first row are taken in clean water (water attenuation coefficient $c=0.1\text{m}^{-1}$). Their exposure times are 0.1 milliseconds. The images (d) (e) (f) in the second rows are taken in turbid water ($c=1.9\text{m}^{-1}$), and the exposure times are increased to 1 millisecond. The images (g) (h) (i) in the last row are taken in extremely turbid water

($c=3.4\text{m}^{-1}$) under the exposure of 4 milliseconds. Due to the laser beam radius, these images show different bright regions (i.e., illuminated area) in their central area. A dash line square is drawn at the same place in each image. The areas inside the square will be used to calculate the irradiance.

The pixels surround by the dash line square are extracted. They form a two-dimensional array. The brightness values in grey part (black bars means no light) are divided by the exposure time. To simplify the representation of irradiance, the divided values are averaged. Each image produces a single irradiance value.

Figure 52 shows the theoretical irradiance curve (solid line) and the measured values (discrete points). The measured irradiances are grouped with the illumination volume settings: $R = 0.01\text{m}$, 0.02m , and 0.03m .

Figure 52. The irradiance projected onto object plane

The figure shows that:

- (1) With the increase of water attenuation, all measured irradiances have similar exponential degradation as the theoretical curve. When water attenuation coefficient is greater than 2 m^{-1} , all measured and theoretical curves have very close values. This indicates that the theoretical model is accurate in turbid water environments.
- (2) The irradiances in the figure are the sum of the direct transmitted component and the forward scattered component. The total irradiance in a wide illumination volume is almost same as the irradiance in a small illumination volume. The curves in the range $c > 1.5 \text{ m}^{-1}$ show the irradiance is independent of illumination volume.
- (3) In clean water ($c < 1.5 \text{ m}^{-1}$), the theoretical irradiances are smaller than the measured values. This is due to the assumption that the forward scattered flux uniformly fills all directions. The assumption is valid in turbid water. The multiple scattering makes scattered light diffuse in all directions. However, the assumption is not valid in clear water where the scattered flux is primarily centralized within the light propagation direction.

4.2.3 The backscattered irradiance

To measure the backscattered flux, the target in Figure 41 is replaced with a light trap. Since the light rays going forwards are absorbed by the trap, the flux received by camera 2 is only from the backscattered light. The backscattered irradiance is:

$$E_{theory_bs} = \frac{P_{bs}}{\pi H^2} = \frac{b_b R^3 E_0}{6 D^2 L^2 c^2} \left[1 - (1 + 2cL) e^{-2cL} \right]$$

In backscattering, the light is reflected back by the particles suspending in water before it reaches the target. So the backscattered light does not carry any information of the target. The images under the illumination of backscattered light only appear in uniform grey. The “grey” images are not identical because the pixel values are different.

Three illumination volumes are used in the measurement. The cross-sectional radius of light beam is set to $R = 0.01\text{m}$, 0.02m , and 0.03m , respectively. Using the similar process in previous section, the pixel values in an image are divided by exposure time, and then averaged to produce a single irradiance value. The theoretical curves and measured values are plotted together:

Figure 53. The backscattered irradiance

Both experimental and theoretical results show that the backscattered irradiance is increased at the beginning when $c < 1.5\text{m}^{-1}$. Then it levels off and gradually degrades. The magnitude of backscattered flux is determined by water condition and the light flux. For example, in highly turbid water, more light rays are scattered, while each ray has very low

energy because of the high attenuation. In contrast, in slightly turbid water, less light rays are scattered, but each ray has high energy.

Similar as the forward projected irradiance, the theoretical backscattered irradiances match with the measured values in turbid water ($c > 1.5 \text{ m}^{-1}$), but they are smaller than the measured value in clear water. This is also due to the assumption in theoretical model that the backscattered flux uniformly distributes in all backward directions. The assumption is valid in turbid water ($c > 1.5 \text{ m}^{-1}$). However, in clean water ($c < 1.5 \text{ m}^{-1}$), the scattered flux concentrates in the light propagation direction, and the assumption is not valid.

4.2.4 The sum of transmitted and backscattered irradiances

When the light trap in the backscattering measurement is replaced with a normal reflective target, the flux received by camera 2 is the sum of transmitted component and backscattered component.

$$E_{theory_camera} = \frac{P_t + P_{bs}}{\pi H^2} = \frac{2\rho_0(R^2 + R^2 L b_f)}{L^2} E_0 e^{-2cL} + \frac{b_b R^3 E_0}{6D^2 L^2 c^2} [1 - (1 + 2cL)e^{-2cL}]$$

Figure 54. Measurement scheme for transmitted and backscattered irradiances

The configuration is plotted in Figure 54. The scene is similar to most practical underwater illuminations. The target is regarded as a Lambertian reflective surface.

The USAF1951 bar pattern is printed on the target for further image contrast analysis. The cross-sectional radius of illumination beam is set to $R = 0.01\text{m}$, 0.02m , and 0.03m , respectively. The images captured in this configuration have similar appearances as that in forward projected flux measurement.

The data acquisition and processing are similar to that in the previous section. The central area of each image is extracted for irradiance calculation. Image pixel values are converted to irradiance by dividing the exposure time. The experimental measurements and theoretical curves are plotted together in Figure 55 for comparison.

Figure 55. Total irradiance received by camera

In highly turbid water ($c > 1.5 \text{ m}^{-1}$), the theoretical curves match the measured irradiance. In clean and slightly turbid water ($c < 1.5 \text{ m}^{-1}$), the theoretical expectation is smaller than the measured values. Similar as the previous experiments, the mismatch in clean water is

due to the assumption that scattered light distributes uniformly in all directions. The assumption is valid in highly turbid water, but not valid in clean water.

4.3 Summary

This chapter presented the experimental setup to verify the theoretical model. A thin laser beam is expanded and then passes through a water tank to illuminate the object. A monochrome CCD camera captures images. Its aperture is set to the maximum size to eliminate the interference speckles, and its exposure time is accurately controlled by a delay generator. Image pixels are converted to optical irradiance by dividing their exposure time.

Underwater environment is simulated in a 0.6 meter long water tank. The light source, camera and target are placed outside the tank. The black cloth covers the side walls of the tank to eliminate the specular reflection from the walls of the tank. The attenuation of light depends on both light path and water turbidity. The water attenuation coefficient is extended from 0.1 m^{-1} (clear water) to 4.0 m^{-1} (extremely turbid water).

Direct transmitted, forward-scattered, and backscattered irradiance components are described in the theoretical model. However, they are unable to be separately measured. Three kinds of irradiances are measured to verify the model:

- (1) Forward projected irradiance, i.e., the sum of direct-transmitted and forward-scattered irradiances,
- (2) Backscattered irradiance,
- (3) The sum of transmitted and backscattered irradiances.

The relationships of Irradiance vs. Water Attenuation are measured and compared with the theoretical curves. The theoretical expectation and measured values match well in highly turbid water (water attenuation $c > 1.5 \text{ m}^{-1}$). However, the theoretical values are smaller than the measurements in clear water. This is due to the assumption made in the theoretical computation. The assumption that the scattered flux uniformly distributes in all directions is valid in highly turbid water ($c > 1.5 \text{ m}^{-1}$), but not valid in clean water where scattered flux concentrates near the beam propagation path.

The backscattered flux is noise and it severely degrades image quality. The theoretical model and the experimental measurements show that the backscattered flux is proportional to the illumination beam size. A wide illumination beam causes high level of backscattered noise in water medium, and then lowers the signal-to-noise ratio in optical images.

Chapter 5 Laser Scanning System and Image Assessment

The effects of the illumination volume on image quality were quantitatively analyzed using the theoretical model and verified by experimental measurements. The result showed that a thinner illumination beam produces less scattered lights. Laser light has extremely thin beam with high power output. When a laser device is the light source, its high-power and concentrated output ensures long-distance transmission of light in water. At the same time, its narrow illumination volume helps to reduce scattered noise. These characters provide thin laser beam great potentials in extending vision range and improving image quality in underwater environments.

Due to the small cross-sectional radius, a stationary and thin laser beam can only cover a very small area. Visible area is determined by the intersection of the field of view of camera and the illumination volume of light source. When a scene is illuminated by a still laser beam and recorded by a camera, there is only a small bright point appearing on a black background in images. To obtain a full image of a target, the laser beam has to illuminate and scan all areas of the scene. Synchronization between lighting beam and camera is required.

Galvanometer scanning system employs a small mirror which is driven by small electrical current. It has very fast scanning speed, but requires precise control. Usually the extremely fast scanning is unnecessary because the movement of URV is not very fast. This chapter describes a low-speed scanning imaging system, which employs a low-power diode-pumped laser and a CCD camera. The 2-D scanning by the laser beam is conducted by a rotating mirror. Each horizontal scan of the beam produces a sub-image, which

subsequently is combined with others to make up a full frame. Due to the speed of scanning, the imaging system needs one or two seconds to get a full frame. The slow scanning system greatly simplifies the hardware configuration. Its illumination beam is adjustable to improve the frame update rate.

The goal of beam scanning is to obtain good images in turbid underwater environments. This chapter will demonstrate how much improvement of image quality can be gotten with beam scanning method. Image contrast indicates details information of a target. It is an objective index for image quality evaluation. To compare contrasts, the MTF (Modulation Transfer Function) chart is applied to analyze an USAF 1951 test pattern. As mentioned in the theoretical model, backscattered noise affects image quality, and the amount of noise is related to both illumination settings and water conditions. To demonstrate the effects of illumination volume on image quality, different sized laser beams will be tested, and their images will be analyzed using MTF calculation.

The laser scanning imaging is a hardware solution to improve underwater imaging capability. As a necessary complement, software processing is helpful in object identification. This chapter will discuss contrast enhancement and adaptive histogram equalization for underwater images.

5.1 Configuration of laser scanning imaging

A prototype of laser scanning system was built up for image acquisition. Its control diagram is shown in Figure 56. A personal computer controls all hardware and software, including mirror rotation, camera exposure, frame capture, and image registration. It starts up two servo motors to drive a rotating mirror. The rotation of the mirror guides a laser beam to do

two-dimensional scans. The computer obtains the projecting direction of the laser beam by decoding motor feedbacks, and then decides proper occasion to trigger the camera. It operates a frame grabber to digitize video signals and store images for real-time or further processing.

Figure 56. Control diagram of the scanning system

The scanning configuration is shown in Figure 57. The scanning mechanism is a sub-system in a commercial scanner which rotates the mirrors to detect distance with laser pulse. A green laser is installed to illumination objects. The beam energy is controlled by a density filter, and the size is controlled by an expander. A floodlight is used to simulate wide-angle illumination in traditional imaging systems.

Figure 57. The optical parts of a laser scanning system

Once the system starts up, the mirror continuously rotates and performs uninterrupted horizontal scans. The vertical rotation is discrete. Each horizontal scan of laser beam produces a long stripe image. When a horizontal scan is finished, the laser beam is indexed by the mirror to the next vertical position and repeats the horizontal scan. The two-dimensional scans produces a series of images, which looks like a stripe, and later are registered together to form a full frame.

The image registration is shown in Figure 58. The stripe images in each scan are correctly registered according to their positions, which are decided by the horizontal and vertical positions of the mirror. The exposure time of one sub-image is 1 millisecond. The image in each scan is captured by a normal CCD camera. There is only a strip of information in one image although the image has full area of 640 x 480 pixels. The strip is extracted for image combination.

The horizontal scan is one direction from left to right due to the mechanism of the mirror. The system has to wait for 50 milliseconds before starting the next image capture.

Figure 58. The image registration in the scanning system

The update rate of full frame is determined by the cycles of scans, which depends on the cross-sectional radius of the laser beam. For example, if the laser beam covers the 640×20 pixels in one scan, the system requires 24 scans (i.e., 24 scan $\times$ 50ms, 1.2 second) to get one full frame (640×480 pixels). A thinner beam requires more scans. The frame update rate of output images can be improved by using a fast scanning mirror, or using less scans with a wide laser beam, or both. In practical applications, the speed of the mirror is limited by its mass, mechanical structure, and the capability of motors. A fast scan faces many difficulties in manipulation and stability. To lower the hardware requirements, our setup discusses a slow scanning scheme.

A successful capture of image requires a camera to cooperate with illumination light. The illumination beam keeps moving in a scanning system. In order to capture a good image, the camera should open its shutter when the illumination beam moves into the desired area, and close the shutter after the beam leaves the area. The scan action of light beam is usually controlled by rotating mirrors or prisms. The mechanical inertia makes it difficult to rapidly change the rotation status. Alternatively, we will change camera action to fit the mechanical scanning.

Most video cameras have fixed frame rate of 30 fps (frames per second). Their shutters are driven by the internal circuits and clocks, which may not coincidentally match the scanning of illumination beam. Our system uses asynchronous reset to ensure the camera capture to exactly match the scanning. Unlike normal cameras which has fixed frame rate of 30 frames/second, a camera with asynchronous reset function is driven by an external signal. In the scanning setup, the camera is driven by the position of the laser beam. It captures one image only when the laser beam moves the desired area. The scheme of video signal is shown in Figure 59.

Figure 59. Asynchronous reset and normal video

The asynchronous reset mode provides a flexible camera operation. The camera shutter can be triggered at anytime to match the motion of the illumination beam. In our setup, the external trigger for the camera is generated according to the positions of the light beam. The position parameters of the motor axis are continuously fed back to a host computer, and then transformed to mirror angles, i.e., illumination directions of the light beam. Once the computer detects that the light beam is projecting to a desired area, it sends a signal to trigger the camera to capture one image. In this way, the system always correctly synchronizes the camera with the light beam regardless the rotation speed of mirror.

5.2 The evaluation of experimental images

Pixel differences based evaluation methods, such as PSNR, have simple principles and calculations, but they are very sensitive to pixel position errors. They are not suitable for our experimental images, which usually have small pixel shift or rotation error during camera capture. In contrast, MTF method can evaluate a single image by analyzing image contents.

Direct contrast measurement is used in the MTF calculation. The USAF 1951 target includes a series of bar patterns whose line pair frequencies (f) are accurately defined. In MTF char plotting, the pixels of every bar pattern are extracted, and then averaged to a one-dimensional data to express the pixel changes at the edge. The maximum (I_{max}) and minimum values (I_{min}) of the edge data are picked up to calculate the modulated contrast $C(f)$.

$$C(f) = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Figure 60. MTF calculation for experimental image

The calculations are shown in Figure 60. Each bar pattern pair has a frequency, f , and the corresponding contrast, $C(f)$. Their results are used to plot a MTF chart.

To discuss the effect of illumination volume on image quality, our experiment uses three settings of light beam to illuminate the USAF 1951 target. The cross-sectional radius of light beam is set as $R = 0.01\text{m}$, 0.02m , 0.03m , respectively. The water turbidity is also adjusted to present the relation between water attenuation and image quality. The obtained images are calculated to produce contrasts and form MTF charts.

Two sets of experimental images are shown in Figure 61. The images in the first row are taken in clean water (attenuation coefficient $c = 0.15\text{m}^{-1}$), and the images in the second row are taken in turbid water ($c = 2.4\text{m}^{-1}$). The image in the last column is a combination of three images because the cross-sectional radius of light beam is too small (radius $R = 0.01\text{m}$) to cover the whole target.

(1). Water attenuation: 0.15m^{-1}

(2). Water attenuation: 2.4m^{-1}

Figure 61. The experimental images for MTF evaluation

The MTF charts of these images are plotted in Figure 62. In each curve, the contrast is degraded when the frequency (line pairs/mm) of a bar pattern increases. The upper three curves are in clean water, and the lower three are in turbid water. The positions of the curves show that the water turbidity predominantly determines the image contrast. The illumination area also affects image contrast. The experimental results match the theoretical expectations. In same water turbidity, a small illumination volume always produces high image contrast. In turbid water, a proper setting of illumination volume can greatly improve image contrast.

Figure 62. MTF of images in clean and turbid water

Image contrast indicates the capability of detail representation. High contrast means low image blur and sharp edge, i.e., good image quality. The MTF method provides an objective evaluation for a single image. It can also be applied to evaluate a whole image system. In our experiments, the MTF method testifies the effects of water attenuation and illumination volume on image quality. In practical applications, it is able to automatically monitor image qualities, and then choose a proper hardware setting (such as the cross-sectional radius of light beam) for a desired image output.

5.3 Image contrast enhancement

Laser scanning imaging is a hardware solution aiming at improving underwater imaging capability. As a necessary complement, image enhancement with software method is significant in object identification. The two kinds of methods are equally important to an imaging system. Laser scanning system can make a dim object visible or detectable, and

software processing method gives output images good appearances to satisfy human eyes or other image processes.

Image contrast index indicates detailed information of an object. High contrast makes object features observable and easy to be identified. Contrast enhancement is one of basic techniques in image processing, and it is widely used in practical applications.

Pixel value is a basic unit in an image. It points out the strength of an optical signal at a unit area. In a grayscale digital image, an individual pixel value can range from 0 to 255. In a RGB color image, a pixel includes three color channels: red, green, and blue. The possible intensity in each channel also ranges from 0 to 255. If all pixel intensities are close to 0, the image looks very dark, and is called underexposure. In contrast, if all intensities are close to 255, the image looks bright, called overexposure. An image has a good appearance when it makes use of the full dynamic range of intensity. In underwater applications, due to wide dim ambient and limited illumination, an image usually presents a dim and low contrast appearance, and its pixel values distribute in a small range. To get a good appearance, the image should be processed by scaling its pixel values.

An image histogram is a chart that shows the distribution of intensities in an indexed or grayscale image (Wang, Wang, & Xu, 2002). It counts the number of pixel assigned to a same intensity. A histogram provides fundamental information of an image. It can be used to choose an appropriate enhancement operation (Gonzalez & Woods, 2002). For example, if an image histogram shows that all intensities are located in a small range, we can use an intensity adjustment function to spread the pixels across a wide range. Histogram equalization is such an adjustment function to transform intensity values and to make the

histogram of the output image approximately match a specified range (Horio, Haraguchi, & Yamakawa, 1999).

In histogram equalization processing, the histogram of an entire image is computed as a reference for the intensity adjustment. The method is not suitable for the images that have great differences of brightness. For example, when an object is under a non-uniform illumination, its image has both very bright and very dark pixels. Once all pixel intensities in this image are scaled by histogram equalization, the information at the bright or dark area may be lost.

An improved method of histogram equalization can solve the problem. It is called contrast-limited adaptive histogram equalization (CLAHE). In this method, a big image is divided into many small tiles, which are individually enhanced with histogram equalization. The tiles later are combined together. To eliminate the artificially induced boundaries, a bilinear interpolation is applied to the borders of the tiles (The MathWorks Inc, 2004). After this processing, the whole image appearance becomes uniform, and the contrasts in partial areas are emphasized.

A comparison of histogram equalization with CLAHE is shown in Figure 63. The original image includes a wide dim area and a very bright spot which is due to specular reflection of target surface. Its histogram shows that most pixel intensities are located in a small range from 20 to 50. When histogram equalization is applied to the image, the whole image becomes bright. The distribution of pixel intensity is extended to a full range from 0 to 255. The image contrast is greatly improved. However, the bright spot area is also enlarged. The area looks like overexposure, and the nearby details are covered by the overexposure

brightness. When CLAHE is applied to the original image, the distribution of most pixel intensities is extended from 20 to 150. The output of CLAHE method has lower image contrast than the output of histogram equalization, but it avoids the overexposure and maintains more details in both bright and dark areas.

Figure 63. Image contrast enhancement

5.4 Summary

In an imaging system, image quality enhancement is implemented by both hardware and software methods. The chapter discussed the design of laser scanning imaging system, including hardware configuration, imaging processing, and image assessment.

The hardware configuration of the scanning system used a thin illumination beam to reduce the backscattered noise. The cross-sectional area of the beam is too small to cover whole target. To get a full view of the target, the beam is directed by a rotating mirror to

implement two-dimensional scans. Its projection direction is monitored by a host computer, and used to trigger the camera exposure action.

The horizontal scans are continuously implemented by the hardware. Each horizontal scan produces a tripe image. Once a horizontal scan is finished, the light beam is indexed to the next vertical position, and the next horizontal scan is repeated. A full frame is obtained by registering many stripe images together. The frame update rate depends on the scan speed and the cross-sectional area of the light beam. If a thin light beam is used to reduce the backscattered noise, more scan cycles will be required and the frame rate will be pulled down.

Image quality describes the presence of visible distortions of an image. MTF is able to evaluate a single image by analyzing image contents. In the experiments, the MTF charts were plotted by calculating the contrasts of the USAF 1951 bar patterns. The result shows that small light beam always produce high image contrast, i.e., good image quality. When water attenuation coefficient is greater than 2.0 m^{-1} , the image contrast indexes under a thin beam illumination (cross-sectional radius 0.01m) are twice of that under a wide beam illumination (radius 0.03m).

Laser scanning system is a hardware method to improve underwater detection capability. Software image processing exalts the specified appearances or features of an image to satisfy various requirements. An underwater image often has dim and low contrast appearances because of barren scenes and caliginous illumination. It can be processed using contrast-limited adaptive histogram equalization (CLAHE). The image is divided

into many small tiles, which are individually processed with histogram equalization and then combined together.

In conclusion, laser scanning is an essential method to make dim objects detectable; and contrast enhancement method significantly improves image appearances and features for identification.

Chapter 6 Conclusions

The thesis discussed how illumination volume affects signal distribution in a parallel light beam illumination. A comprehensive theoretical model was built to reveal the effect of the geometric size of illumination beam, which affects the distribution of signal and noise but was ignored in many existing models. It showed that backscattered irradiance is proportional to cross-sectional radius of light beam. The model was verified with experimental measurements and applied in a prototype of laser scanning system. In practical applications, the model can determine a proper illumination volume according to water turbidity, and optimize hardware configurations of vision systems. Image quality was evaluated by MTF (modulation transfer function) charts. The result consisted with the expectation of the model. Contrast-limited adaptive histogram equalization (CLAHE) was applied to experimental images to improve image appearances.

Among various imaging approaches, optical vision is an irreplaceable scheme to obtain high resolution and intuitive information. One main obstacle in underwater optical imaging is signal attenuation due to water absorption and scattering. Because of the inherent properties of water medium and suspending particles, optical signal is severely degraded during light propagation. Scattering is the major problem as it adds significant noise to images, and then greatly degrades the signal-to-noise ratio in images.

Laser scanning system and range-gated system can effectively eliminate or reduce the scattered noise. As scattered noise is from the common volume between light beam and field of view of camera, a laser scanning system uses a thin illumination beam to minimize the common volume and reduce the amount of received noises. A range-gated system uses

an extremely short laser pulse to illuminate objects. It carefully delays camera shutter to avoid the noise, which is reflected by suspending particles and returns back earlier than desired lights. The two systems have been proved useful in underwater vision range improvement. However, they usually have huge sizes and consume great electrical power. They are not suitable for small URVs, which provide very limited load and power supply. This thesis proposed a low-speed scanning method. Its low-powered light beam has an alterable illumination volume to fit different water conditions.

A mathematical model was built to provide comprehensive and precise estimation of light flux in a continuous illumination. It assumed that forward and backward scattered fluxes uniformly fill all forward and backward directions. Multiple scattering is dominating in highly turbid water. The model scattered flux through the light propagation path. Light propagation of was divided into two stages: from the light source to the object, and from the object to the camera. Light flux in each stage was regarded as a linear superposition of transmitted, forward-scattered, and backscattered components, which were individually calculated with the volume scattering function and Bouguer's law (i.e., signal exponential attenuation with distance).

The model differs from the existing models because it discusses the effect of geometric size of light beam on light flux. It quantitatively revealed how illumination volume affects the distributions of flux components. The direct transmitted flux is greater than the backscattered flux in clean water, but it drops faster than the backscattered component when water turbidity increases. When a light beam is being expanded, the total fluxes received by a camera are increasing, and backscattered component increases faster than

correctly transmitted component. When a wide illumination beam is used in turbid water, scattered noise may exceed signal and make objects undetectable.

The model can be used choose a proper illumination volume in a turbid water environment. Since scattered noise is related to both illumination volume and water turbidity, to get a satisfactory image, illumination beam should be adjusted to fit different water conditions. In a laser scanning system, an illumination beam should be concentrated to get further vision range in turbid water, and expanded to speed up scanning processing in clean water. The variable illumination beam balances the image quality and scanning time. It also efficiently utilizes the power of the laser beam.

The theoretical model was verified with experiments. Illumination scenes were simulated in a 0.6 meter long water tank. Light attenuation always depends on both light path and water turbidity. The coastline seawater is about 1.5 m^{-1} . To compensate the short length of water tank, water attenuation coefficient ranged from 0.1 m^{-1} (clear water) to 4.0 m^{-1} (extremely turbid water) in experiments.

Although direct transmitted, forward-scattered, and backscattered flux components were described in the theoretical model, these components were unable to be separately measured in practice. Three kinds of irradiances were measured by a monochromatic CCD camera: forward projected irradiance, backscattered irradiance, sum of transmitted and backscattered irradiances.

The relationships of Irradiance vs. Water Attenuation were measured and compared with the theoretical curves. The same change trends of the measured values and theoretical computation proved the accuracy of the model. The experimental measurements are

compared with the theoretical expectations in highly turbid water where water attenuation coefficient is greater than 1.5 m^{-1} . In slightly turbid water, the theoretical values are smaller than the measurements. The theoretical computation assumes that the scattered flux uniformly distributes in all directions. This assumption is only valid in highly turbid water. In practical scenes, scattering represents obvious directionality in clear water. The scattered flux is primarily centralized within a small cone angle along the light axis. In turbid water, the directionality gradually disappears due to the effect of multiple scattering.

The model was applied to a prototype of laser scanning system. A thin illumination beam was employed to reduce the scattering noise. The cross-sectional area of the beam was too small to cover whole target. To get a full view of the target, the beam was directed by a rotating mirror to implement two-dimensional scans. Its projection direction was monitored by a host computer, and used to trigger the camera exposure action. Asynchronous reset function of camera ensures the synchronization between camera capture action and beam scanning. Each horizontal scan produces a long tripe image, which is registered together with other stripes to form a full frame. The frame update rate depends on the scan speed and the cross-sectional area of the light beam. In turbid water, a thin light beam should be used to reduce the backscattered noise, then more scan cycles will be required, and the frame rate will be reduced.

The frames of scanned images were evaluated by MTF (modulation transfer function) method, which is able to provide high precision and comprehensive representation of imaging performance. MTF charts were plotted by calculating the contrasts of the USAF 1951 bar patterns. The result showed that a small light beam always produced high image contrast, i.e., good image quality. When water attenuation coefficient is greater than

2.0m^{-1} , the image contrast indexes under a thin beam illumination (cross-sectional radius 0.01m) are twice of that under a wide beam illumination (radius 0.03m).

Laser scanning system is a hardware method to improve underwater detection capability. It makes object detectable. Software image processing is able to give images good appearances to satisfy various requirements. An underwater image often has dim and low contrast appearances because of barren scenes and caliginous illumination. In CLAHE (contrast-limited adaptive histogram equalization) enhancement, an image is divided into many small tiles, which are individually processed with histogram equalization, and then combined together. The method significantly improves image contrast index and clarifies identification features in an image.

In conclusion, this research studied the effect of illumination volume on camera imaging. A laser scanning system was shown to be able to improve signal-to-noise ratio and make dim objects detectable, and that its illumination beam plays an important role in reducing scattered noise and improving image quality in turbid water environments.

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