Backscattering phenomena on range-gated imaging in short-range turbid water media

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THE BACKSCATTERING PHENOMENA ON RANGE-GATED IMAGING IN SHORT-RANGE TURBID WATER MEDIA

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2006

The Backscattering Phenomena on Range-Gated Imaging in Short-Range Turbid Water Media

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

2006

To
My parents

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Table of Contents

<i>Title Page</i>	<i>i</i>
<i>Acknowledgements</i>	<i>ii</i>
<i>Table of Contents</i>	<i>iii</i>
<i>List of Symbols</i>	<i>vii</i>
<i>List of Abbreviations</i>	<i>xiii</i>
<i>List of Figures</i>	<i>xvi</i>
<i>List of Tables</i>	<i>xviii</i>
<i>Abstract</i>	<i>xix</i>
Chapter 1 Introduction	1
1.1 Introduction	1
1.2 Range-Gated Operating System	4
1.2.1 Research and development of range-gated imaging system	6
1.2.2 Laser	10
1.2.3 Camera	11
1.2.4 Applications	11
1.2.5 The theoretical analysis of range-gated imaging system	12
1.3 Objectives and Scope	12
1.4 Organization of the Thesis	15
1.4.1 General research methodology	16
1.4.2 Thesis outline	17
Chapter 2 Literature Review	19
2.1 Oceanography	19
2.1.1 Scattering	20
2.1.2 Absorption	22
2.1.3 Underwater visibility	23
2.1.4 Image quality evaluation	24
2.2 Time Dependent Radiative Transfer Equations	26
2.3 The Monte Carlo Method	28
2.3.1 Introduction of variable step sizes Monte Carlo algorithm	30

Table of Contents

2.3.2	Information generator - photon propagation	32
2.3.3	Input – photon generations	34
2.3.4	Input - system geometries	35
2.3.5	Input - seawater phase functions and IOP	35
2.3.6	The information processor	36
2.3.7	Convolution – TPSF and pulse length	36
2.3.8	MCM Validation	37
2.4	LIDAR Equations	38
2.5	Range-Gated Imaging Models	42
2.5.1	Computer modelling by J. S. Jaffe	45
2.5.2	Imaging model for range-gated imaging systems	46
2.5.3	Generic LIDAR model by McBride et al	47
2.5.4	Computer based underwater imaging analysis	48
2.6	Chapter Summary	49
Chapter 3	<i>The Monte Carlo Method for Reflected Image Temporal Profile (MCRITP)</i>	51
3.1	Introduction to Reflected Image Temporal Profile (RITP)	51
3.2	The algorithm of MCRITP	55
3.3	Validation of MCRITP	57
3.4	Chapter Summary	64
Chapter 4	<i>System Analysis and Laboratory Set Up</i>	66
4.1	System Introduction and Timing Diagram	66
4.1.1	General layout	67
4.1.2	Timing diagram	69
4.2	System Components	71
4.2.1	PCU and Laser head assembly	72
4.2.2	Delay generator	74
4.2.3	Xybion camera	75
4.2.4	CCU control unit	77
4.2.5	Photo detector	79
4.2.6	Frame grabber, the oscilloscope and attenuation meter	79

Table of Contents

4.3	The Testing Target in Simulated Water Condition	80
4.4	Quantitative Image Quality Assessment	81
4.4	Performance Evaluation of Range-Gated Imaging System	84
4.5	Chapter Summary	85
Chapter 5	<i>Backscattering Noise Analysis Within Reflected Image Temporal Profile (RITP)</i>	89
5.1	Introduction	89
5.2	Backscattering Noise within RITP	90
5.3	Target Signal and Signal Scattered Noise	94
5.4	Signal to Backscattering Noise Ratio within Actual RITP	95
5.4.1	Gate timing delays	96
5.4.2	Shorter gate durations	102
5.4.3	Shorter pulse lengths	102
5.5	Chapter Summary	104
Chapter 6	<i>Image Processing of Range-Gated Images</i>	107
6.1	Introduction	107
6.2	Image Enhancement Schemes	114
6.2.1	Contrast stretching	114
6.2.2	Contrast Limited Adaptive Histogram Equalization	115
6.2.3	Illumination-reflectance model	115
6.2.4	Homomorphic filtering	116
6.3	Discussions on Image Enhancement Schemes	116
6.4	Image Fusion Schemes	119
6.5	Quality Measure for Image Fusion	119
6.6	Discussions on Image Fusion Schemes	122
6.7	Chapter Summary	125

Chapter 7	Conclusions	127
7.1	Contributions	127
7.1.1	Formulation for backscattering noise within RITP	127
7.1.2	Verifies tail-gating concept analytically	128
7.1.3	Gate time and pulse length analysis	128
7.1.4	Performance of this system in laboratory condition	129
7.1.5	Framework for gated images in multi-target or extended target condition	129
7.2	Future directions	130
7.2.1	System Engineering	130
7.2.2	Performance evaluation	130
7.2.3	The Monte Carlo Method	131
7.2.4	Multi-target or extended target analysis	132
7.3	Concluding remarks	132
List of Publications		134
Reference		135
Appendix A	Mathematical Definitions for Ocean Optics	155
Appendix B	Monte Carlo Method	157
Appendix C	The Equipment Setting	161
Appendix D	More Results on Image Enhancement Schemes	163

List of Symbols

(The symbols are defined as below, unless it is otherwise specified in the context)

A	the receiver area
A_p	non-sensor noise image
A_n	with sensor noise image
$A^{IF}(i,j)$	relative orientation value between image 1 and fused image
$A_x(z, \tau_l)$	complex function of Gamma-spread multi-path scattered energy
a	absorption coefficients [m^{-1}]
B	scattering coefficient [m^{-1}]
B_f	forward component of the total scattering coefficient B
C	total attenuation coefficient [m^{-1}]
C_l	LIDAR constant
$c_m(i,j)$	multiplicative component
$c_a(i,j)$	additive shading component
D	water depth
$E(t_2-t_1)$	the integrated backscattering energy
$E'(t_2-t_1)$	the integrated target signal
$E_d(x, y)$	irradiance due to non-scattered light from the object
$E_g(x, y)$	irradiance due to forward scattered light from the object
$E_{bt}(x, y)$	irradiance due to backscattered light from the water
$f(r)$	function of the receiving system and geometrical effects
$f(t)$	TPSF of a medium
f_n	f-number of camera lens
F	focal length
F_{fused}	Fused image
f	spatial frequencies

f_c	half of the highest frequency of ideal image
$f_I(i,j)$	reflectance function
$G(x,y)$	point spread function
$G^{IF}(i,j)$	relative strength value between image 1 and fused image
g	the asymmetric parameter of scattering indicatrix
g_{HG}	Henyey Greenstein coefficient
$g_I(i,j)$	edge strength
$h(p)$	the corresponding grey level histogram
H	airborne altitude of receiver and transmitter
H_0	the energy per pulse of a laser [mJ]
$I(\vec{x};t;\xi;\lambda)$	the radiance [$\text{Wm}^{-3}\text{sr}^{-1}\text{nm}^{-1}$]
I^E	bi-static elastic scattering radiance
I^I	bi-static inelastic scattering radiance
I^S	source radiance
$I_8(\vec{x};t;\xi)$	instantaneous excitation
$I_0(t)$	source function
$\dot{I}(i,j)$	pixel values of the investigated image
$I(i,j)$	pixel values of the idealized image
$\text{ISBR}(t)$	Instantaneous Signal to Backscattering Ration
I'_m	mean pixel value of investigated image
I_m	mean pixel value of idealized image
$I_{cl}(i,j)$	pixel values of ideal image under absence of shading
$I_{fd}(i,j)$	pixel values of fused image
$I_{pr}(i,j)$	pixel values of perfectly fused image
$I_t(i,j)$	pixel values of individual image before the normalization process
K	a random number drawn form the unit interval between 0 and 1

K_d	down-welling irradiance attenuation coefficient
k_n	scaling factor
m, n	the water refractive index
$MTF_{sys}(f)$	the MTF of the testing image
$MTF_{dl}(f)$	the modulation transfer function of the diffraction limited image
M	number of rows of the images
N	number of rows of the image
N_s	noise-seed signal
n	signal to noise ration in dB
$OSBR(t_1, t_2)$	Overall Signal to Backscattering Ration
p	a grey level with a range of $(0, P)$
p_m	mean value of the grey level
$P(r)$	the probability of a unit of energy received by the receiver
$P_0(x, y)$	source power function
P_0	the average pulse power
$P_i(t)$	the convolution between the $S_i(t)$ and $P_0(x, y)$
$P_{ss}(r)$	power received from single backscattering event of a laser pulse
$P_t(t)$	total measured LIDAR signal
$P_{BSN}(t)$	the single and multiple backscattering noise from turbid medium
$P_S(t)$	the target signal
$P_{SMM}(t)$	the signal scattered noise
$\langle P_{bottom}(\zeta) \rangle$	the convoluted bottom return
$P_{bottom}(\zeta)$	temporal point spread function of the sea bottom
P_{fused}	given fusion process
Q	energy of an impulse output from the transmitter
$Q_g^{1F}(i, j)$	perceptual edge strength loss of information in F , from image 1
$Q_\alpha^{1F}(i, j)$	perceptual edge orientation loss of information in F , from image 1

List of Symbols

$Q_p^{123/F}$	Petrovic's fusion quality index for a given fusion process P that operates on all three images
R	orthogonal distance from the travelling wavefront
R	total propagation distance
$R_m(t)$	normalized pulse response function of a receiver
R/π	Lambertian seabed reflectivity
R_i	distance from a point in camera to the centre of the backscatter slab
$R_T(t)$	total reflectance
S	Sensitivity function of a receiver
$S_i(t)$	Temporal Point Spread Function (TPSF)
s	distance
s_I	multiplicative factor
$s_I^x(i,j)$	the output of the horizontal Sobel operator
$s_I^y(i,j)$	the output of the vertical Sobel operator
S_f	final sensitivity (foot candle, fc)
S_i	camera's ungated sensitivity
T_f	readout rate of the camera
T_g	camera's gate duration in ms
t	time
t_0	pulse length exerted to the medium
t_1	light scattering delay or camera close time
t_2	mean time of flight between interactions or camera gate width or camera open time
t_3	effective gate time
T	number of images in a fusion scheme
$T_{rcvr}(\tau_I)$	simple multiplier function related to $P_0(t)$
T_{atm}	transmission coefficient of the atmospheric

T_{aw}	the transmission coefficient water medium
T_1	delayed period for the lasing event
T_2	delayed period output from DG535
T_3	delayed period in the camera itself
T_4	delayed period between the lasing and the return image signal
T_5	delayed period between the lasing signal to the frame grabber
T_{lens}	Lens transmittance
v_0	light speed in vacuum
$v=v(\vec{x};t;\lambda)$	the speed of light in the medium
$\vec{x}$	position vector
z_0	effective source approximation ($z_0=1/\mu_{tr}$).
α	Field Of Illumination, or angular subtense [$^\circ$]
$\alpha_l(i,j)$	orientation information
β	the phase function characterize the scattering from ξ to ξ' .
$\beta(\pi,r)$	volume backscattering coefficient at range r
∂l	delta distance travelled by a photon
λ	wavelength (nm)
ξ	directional unit vector (into the unit volume)
ξ'	directional unit vector out from the unit volume
$A = B/C$	albedo of single scattering
φ	azimuthal angle
ψ	scattering angle out of ξ axis
$\phi(x,y,z)$	the output fluent rate from a complete simulation
$1/r^2$	spatial decay of the radiation
$\sigma(r')$	the atmospheric extinction coefficient
σ_g	Parameter of sigmoid function for edge strength (Equation 6.12)

List of Symbols

σ_α	Parameter of sigmoid function for orientation strength (Equation 6.13)
$\otimes$	the convolution in time domain
η	<i>receiving</i> system efficiency
τ_l	multi-path time
$\langle \tau \rangle$	mean multi-path time
τ_H	the maximum desired values of $I(i,j)$
τ_L	the minimum desired values of $I(i,j)$
ζ	virtual distance in the water medium to represent the multiply backscattered energy from the respective depth ($r_o + v\pi/2$)
Ω_{rcvr}	receiver field of view
ω	angular frequency
ω_x	horizontal spatial frequencies
ω_y	vertical spatial frequencies
ω_0	cut-off frequency
θ	the angle between the reflected plane with camera line of sight
θ_0	mean scattering angle of a phase function
ρ	source receiver separation
ρ_l	an offset term
ρ_2	Image quality index by Li et al
Γ_g	Parameter of sigmoid function for edge strength (Equation 6.12)
Γ_ω	Parameter of sigmoid function for orientation strength (Equation 6.13)
κ_g	Parameter of sigmoid function for edge strength (Equation 6.12)
κ_ω	Parameter of sigmoid function for orientation strength (Equation 6.13)

List of Abbreviations

ABC	Automatic Brightness Control
AC9	Attenuation Meter
AEL	Accessible Emission Limits
AL	Attenuation Length
AOP	Apparent optical properties
BP	Backscattering Peak
BSF	Beam Spread Function
CCTV	Closed Circuit Television
CCU	Camera Control Unit
CLAHE	Contrast Limited Adaptive Histogram Equalization
CNR	Contrast-to-Noise Ratio
CRG	Contrast Radius of Gyration
CW	Continuous Wave
DA	Diffusion Approximation
DE	Diffusion Equations
DIAL	Differential Absorption LIDAR
DHT	Difference Histogram Threshold
DREV	Defence R&D Canada Val Cartier
DWF	Discrete Wavelet Frame
EIGT	Effective integration gate time
FOI	Field of Illumination (angular subtense)
FOV	Field of View
FPGA	Field Programmable Gate Array
FWHM	Full Wave Half Maximum
GUI	Graphical User Interfaces

List of Abbreviations

ICCD	Intensified Charge Coupled Device
IG	Information Generator
InGaAs	Indium Gallium Arsenic
IP	Information Processor
IOP	Inherent optical properties
ISBR	Instantaneous Signal to Backscattering Noise Ratio
LANL	Los Alamos National Laboratory
LIDAR	Light Detection And Ranging
LRG	Laser Range Gated
LSI	Large Scale Integrated video circuits
LUCIE	Laser Underwater Camera Image Enhancer
MCM	Monte Carlo Method
MCP	Multi-Channel Plate
MCRITP	Monte Carlo for RITP
MF	Modified Fidelity
MSR	Modified Strehl Ratio
MTF	Modulation Transfer Function
Nd:YAG	<u>Neodymium-doped Yttrium Aluminum Garnet</u>
NEC	Noise Effective Cut-off frequencies
NSWC	Naval Surface Warfare Centre
NTU	Nanyang Technological University
OTF	Optical Transfer Function
OSBR	Overall Signal to Backscattering Noise Ratio
PCF	Performance Comparison Figure
PCU	Power/Cooling Unit
pdf	probability density function
PSF	Point Spread Function

List of Abbreviations

PTF	Phase Transfer Function
RITP	Reflected Image Temporal Profile
ROV	Remote Operated Vehicle
RTE	Radiative Transfer Equations
SBR	Signal to Backscattering noise Ratio
SNL	Sandia National Laboratory
SR	Strehl Ratio
SSP	Surelite Separation Package
TDI	Time Delay and Integration
TPSF	Temporal Point Spread Function
TTHG	two-term Henyey Greenstein
TTL	Transistor-Transistor Logics
USAF	United State Air Force
UWLIS	Underwater Laser Imaging System
VEUS	Visibility Evaluation of Underwater Systems
VSF	Volume Scattering Function
WAPS	Weighted Average of Power Spectrum

List of Figures

Figure 1.1	Range-gated imaging system overview in spatial domain	5
Figure 1.2a	Non-gated temporal backscatter noise integration	6
Figure 1.2b	Range-gated temporal backscatter noise rejection	6
Figure 1.3	Research methodology of NTU range-gated imaging system	16
Figure 2.1	General research frame work for MCM algorithms	29
Figure 2.2	Basic variable step size Monte Carlo algorithm	33
Figure 3.1	Reflected Image Temporal Profile	52
Figure 3.2	Simple illustration of photon groups derived from Equation 3.1	53
Figure 3.3	MCRITP	56
Figure 3.4	MCRITP for Wilson's approach	58
Figure 3.5	Comparison of MCRITP results with Wilson's results	59
Figure 3.6	MCRITP for Yaroslavsky's model	60
Figure 3.7	Comparison of MCRITP results with Yaroslavsky's model	61
Figure 3.8	MCRITP for experimental validation	62
Figure 3.9	Comparison of MCRITP and experimental results	64
Figure 4.1	General equipment layout (Picture)	67
Figure 4.2	Current equipment schematic diagram	68
Figure 4.3	Range-gated imaging system operation diagram	69
Figure 4.4	Timing diagram of normal range-gated system	70
Figure 4.5	General design layout	72
Figure 4.6	Laser head & diverter assembly	73
Figure 4.7	Delay Generator	74
Figure 4.8	Xybion camera	76
Figure 4.9	CCU control unit	78
Figure 4.10	Quantitative Image Quality Indexes for turbid images	84

List of Figures

Figure 4.11	Basic design considerations of range-gated imaging system	86
Figure 4.12	Actual experiment condition	87
Figure 5.1	Comparison of Equation 5.4 with 3m fixed upper limit and Without fixed upper limit	93
Figure 5.2	RITP and target reflected energy for 3m target distance	95
Figure 5.3	Recalculated SBR in increased turbidity	97
Figure 5.4	Images taken on various RITP regions for range gated ULIS	100
Figure 5.5	Maximum ISBR and OSBR in increased outgoing pulse lengths	103
Figure 6.1	Experiment setup for extended or multiple targets condition	108
Figure 6.2	Sequentially gated images from closest to furthest targets	109
Figure 6.3	RITP for 1.8m and 1.1m target distance	110
Figure 6.4	General image fusion framework for range-gated images	113
Figure 6.5	Homomorphic filter	116
Figure 6.6	Image quality indexes for enhancement schemes	118
Figure A1	Phase functions normalized at 90^0 for various water models	156
Figure B1	MCRITP (Similar to Figure 3.2)	157
Figure B2	Monte Carlo coordinate system	159

List of Tables

Table 1.1	General advanced imaging technique	3
Table 1.2	Selected research group of range-gated imaging system	7
Table 4.1	Comparison of gated and non-gated images in increased turbidity	85
Table 5.1	Camera gated opening time in increased turbidity	99
Table 6.1	Enhanced gated images in increased turbidity	117
Table 6.2	Comparison of arithmetic and “Choose-max” fusion methods	123
Table 6.3	Comparison of arithmetic and “Choose-max” fusion methods with strong noises after image enhancement stage	124
Table D1	More results on image enhancement schemes	163-164

Abstract

Clear image acquisition in turbid seawater environment has always been a matter for concern in various underwater inspection and intervention tasks. This is particularly true for Underwater Robotic Vehicle (URV) missions in turbid waters. Among various imaging approaches, optical imaging system offers higher resolution and faster frame rate compared with sonar imaging systems. The focus of this research aims to reduce the effects of image degradation due to optical noise resulting from scattering of the intervening turbid medium. In the context of our application, there is a need to acquire clear target images that is within 3 m range. A range-gated imaging system reduces most of the backscattering noise from the turbid medium. Subsequently, optimization was on fine-tuning the image quality based on control parameters and image processing techniques.

The output image quality was correlated to the actual performance of the system by various quantitative image quality indexes. The Modified Fidelity (MF) index evaluates the system performance using the United State Air Force (USAF) target images. By increasing the water turbidity with Mylanta[®], the laboratory trials show an improvement of over 40% (MF) for images obtained using gated over non-gated imaging.

A number of parameters affect the final image quality. However, the analysis of backscattering phenomena in a turbid media is indispensable in the selection and determination of appropriate sensors as well as to ascertain the overall image processing performance. A novel model was proposed to describe the backscattering noise variation within the Reflected Image Temporal Profile (RITP) in a near target condition. This is a modification of Falk's LIDAR (Light Detection and Ranging) equation and the superimposition of backscattering noise with reflected target irradiance in the time domain.

The modified formulation shows better reduction of backscattering noise compared to the target signal towards the tail of RITP. In order to examine the diverged light pulse propagation within a semi-infinite medium, the Monte Carlo method simulates the stochastic nature of photon particles propagation in a homogeneous turbid medium. The simulation model was verified using Yaroslavsky's model and experimental results within 20% relative errors. Under near target turbid condition, it shows tail RITP gated images are better than front RITP gated images. This agrees well with the theoretical model and Witherspoon's observations from their range-gated imaging system. The formulation explains why shorter pulse length and/or gate duration will achieve better Signal to Backscattering Noise Ratio (SBR) than combinations at longer gate durations and pulse length.

For multi-target or extended target situations, the range-gated images have been sequentially gated in increasing range to cover all targets within the Field Of View (FOV). This thesis provides a preliminary analysis of multi-gated image characteristics in incremental gate timing as a means of overcoming the Depth of Field (DOF) limitation. A novel fusion framework is proposed to fuse individually gated images together to form a complete DOF image. This provides both image enhancement and fusion to integrate the enhanced portions of multi-target or extended target images. For minimum backscattering noise images, the Contrast Limit Adaptive Histogram Equalization (CLAHE)-"Choose-Max" fusion scheme is demonstrated.

In conclusion, RITP is established. A modified model is introduced to verify the tail-RITP gating technique analytically. This has also resulted in theoretical examination of gate time and pulse length effects for better image quality from the perspective of SBR. For multi-target or extended target condition, the gated images could be fused with incremental gate opening time.

CHAPTER 1

INTRODUCTION

This chapter identifies the objectives and motivations of this research project. It first establishes the domain of the research focus in general underwater imaging systems for turbid working environment. Among various choices of imaging approach, light optical range-gated imaging system is one of the preferred choices for sub-sea inspection and repair missions. The analysis focuses on the optimization of range-gated imaging systems to minimize the backscattering noise from turbid environment. This analysis has subsequently motivated the research as defined in the later sections. The last section describes the research methodology.

1.1 Introduction

Clear image acquisition in scattering media, like in a turbid seawater environment, has always been a matter for concern in various underwater inspection and intervention tasks. The purpose of underwater imaging is to fulfil various tasks for human operators of underwater robots or autonomous systems. This involves various users, such as navy, ecologists, geo-morphologists [1], etc. From an application point of view, there is no doubt we need underwater vision for Remotely Operated Vehicle (ROV), pipeline inspections [2], object avoidance or recognition [3], grasping, docking, seabed reconstruction, underwater surveillance, inspection, cable maintenance [4], archaeological surveys [5] etc. Advances in technology have offered multiple choices of imaging channels [1] that include sonar, optical imaging and their combinations [6], [7].

Those imaging systems can be categorized under numerous criteria. Generally, they are grouped into active or passive systems. For both sonar and optical systems, the active systems take advantage of a user-generated source of energy. Among common used imaging approaches, sonar offers longer range but lower resolution images [8] whereas the light optical system offers better resolution and fast frame rate [1], [9] to achieve higher information content. Thus, it will be advantageous to use light optical imaging system as our primary vision device for dexterous underwater robotic vehicles in confined inspection and repair missions.

However, images associated with underwater light optical imaging systems are frequently degraded due to various noises and attenuation of target signal [10], [11]. In turbid environments, the main causes of image degradation are absorption and scattering effects [1], [9], [13]. The absorption effect reduces the signal strength, and the latter effect reduces both signal strength and image resolution. In a typical application, the underwater imaging system employs a closed circuit television (CCTV) camera and a wide-angle illumination source. These systems are limited primarily by backscattering effect, particularly when the source and receiver are in close proximity [9].

Various imaging techniques are available to improve the underwater visibility and image quality. These techniques aim primarily to discriminate backscattering noise from turbid medium using temporal or spatial methods (or both), such as spatial filtering, time gating, streak tube camera, etc. Table 1.1 summarizes common techniques deployed in underwater applications. Each of them possesses their respective advantages and disadvantages. A technique found useful in one application may not necessarily be better for another. The user must recognize the type of design and application problem before they select an appropriate technique to enhance underwater visibility and image quality.

From Table 1.1, increasing the separation of illuminator and receiver together with indirect illumination are not preferred, as they do not produce high quality images or better power efficiency. The most widely used industrial advanced imaging techniques are continuous laser line scanning (i.e. items 3 & 4 of Table 1.1), and pulsed gated imaging systems (i.e. items 5 & 6 of Table 1.1). The synchronous scanning system aims to compose two-dimensional images with rough range estimation, while the 3D scanning system improves the accuracy of range data by triangulation and mapped with target reflectance maps. Range-gated imaging system forms enhanced two-dimensional images while streak tube cameras enable time resolved three-dimensional high-resolution mapping. Those imaging techniques could be accomplished with polarizer/filter lens that would possibly discriminate the backscattering noise from the actual target signal. Besides, the coherent imaging technique is sensitive to object shape and contour. The application is still in development phase for actual industrial applications.

	Technique	Advantages	Disadvantages	Reference
1	Increasing separation of illuminator and receiver	Low cost	Need large system spacing and low visibility	[15]
2	Indirect illumination	Low cost	Inefficient and low visibility	[5][16]
3	Synchronous scanning (point projection or single line projection)	Enhanced images	Affected by platform or target motion. Complex mechanism.	[13][17]
4	3D scanning (structured laser line/beam)	Better range data	Affected by platform or target motion. Complex mechanism.	[1][18]
5	Range/time gating (Burst illumination)	Enhanced images & motion insensitive	Higher cost	[19]
6	Streak tube camera/ Time-resolved camera	Enhanced 3D map	Higher cost and higher complexity	[20]
7	Polarization discrimination	Low cost	Limited effect. Mostly combined with other techniques.	[21]
8	Coherent imaging	Sensitive to object contour & shape	Still in development phase	[22]

Table 1.1 General advanced imaging techniques for various applications in turbid media with backscattering issues as the dominant noise effect.

Among those techniques listed in Table 1.1, the range-gated imaging concept is normally preferred not just due to its high range and high-resolution performance, but also because of its robustness in terms of motion insensitivity. Especially in harsh underwater conditions, the images are normally distorted due to the flotation effect of targets and system motions. Thus, this advantage has made range-gated imaging system a preferred choice in underwater applications. Nevertheless, it is also believed to possess some other advantages, such as robustness in terms of size, weight, power consumption, ambient light immunity, and viewing flexibility [14]. These advantages are of prime consideration in the application of diver and URV. Thus, this project chooses range-gated imaging techniques as the choice of research for a URV viewing system. The focus of this research aims to investigate the performance of a range-gated imaging system and its potential optimization schemes to achieve higher underwater image/video quality.

1.2 Range-gated operating system

The working principle of the range-gated imaging system is similar to the pulsed LIDAR technology. LIDAR stands for **L**ight **D**etection **and** **R**anging. The post-processing of LIDAR data could be as simple as just points of target range calculation, or as complex as fused LIDAR-derived elevation data with digital imagery sources [25]. On a functional level, it is typically understood as the technologies to produce digital elevation models or maps (for land and undersea) by using laser, positioning, and photo-detection equipment [26]. This technology is particularly useful for collecting high-resolution data that were difficult or impossible to obtain by other means. Nevertheless, it is also useful for the detection of frequency shifts (Doppler LIDAR), depolarization, and backscattering intensity from multiple wavelengths. One of the examples is its application in turbid conditions such as coastal water bathymetry surveys. The laser pulse at appropriate wavelength can penetrate up to 50-60 meters of water depth. On their returning paths, an airborne bathymetry system could discriminate the scattering noise from water surface and water medium temporally and retrieve the seabed reflectance [27], [25].

Similarly, a range-gated imaging system [28] achieves better image quality by temporally discriminating the target reflectance from backscatter and its associated noise. Figure 1.1 illustrates this principle in the spatial domain. It basically consists of a pulsed laser system, a control/synchronous logic and a high-speed gated camera. A range gating process starts when the laser sends a pulse onto the target/object. As the light travels, it is absorbed and scattered. The camera gate is kept closed at all times until the laser pulse returns to the camera after hitting the target. Once the laser pulse is over, the camera gate closes again to avoid any scattering effect interfering with the original image. It should be noted that the camera gate is open or closed selectively based on prior information about the target distance or target location. In the turbid media, the information could be fed into the range-gated imaging system from various means, such as manual determination, return image pulse estimation, a LIDAR system and from other sensors [7]. This is the drawback of range-gated imaging system in difficult imaging conditions.

Temporally, the range-gating concept is shown in Figure 1.2. After the emission of a short illumination pulse, the light returning to the receiver as a function of time is shown. Figure 1.2a shows that a non-gated receiver will predominantly collect

backscatter. However, as in Figure 1.2b, if the receiver is left off until time t_1 , corresponding to the round trip time of the illumination pulse to the target and back, and then turned on for a short time δt , corresponding to the length of the illumination pulse, then the signal to noise ratio dramatically increases.

It is commonly accepted that the working principle of a range-gated imaging system is similar to the pulsed LIDAR technology [20], but with different design objectives. A range-gated imaging system focuses on retrieving the content of the target reflected pulse at a predetermined target distance to form a two-dimensional image. LIDAR aims to capture the returning signals for time-of-flight computation of target distances. Thus, it is natural to observe recent advance systems, such as LIDAR imaging systems [23] that have combined both systems together to acquire large field of view images and correlated information in terms of spectral images and range maps. Some research groups have also combined it with scanning systems used for airborne LIDAR surveying missions [24].

1.2.1 Research and development of range-gated imaging system

Range-gated imaging systems have been developed since the 1960s [29], [30]. The core contributions to the range-gated imaging systems are mainly due to the advances in laser and intensifier gated semiconductor cameras [2] in the later years. Nowadays, the technique has been used in various applications, such as high speed photography [31], medical imaging [32], underwater imagery, airborne scanning/ bathymetry [33] etc. Because of these different applications, this technique is sometimes named differently, such as burst illumination for long-range identification, time gating for trans-illumination systems or a high speed imaging system, etc. Basically, they refer to the same imaging concept. In turbid water imaging, it proves to be better, and some developers claimed it had up to 6 times the target distance detected than by normal active imaging system [34]. The-state-of-the-art has shown trends of utilizing other imaging techniques into range gating theory (or vice versa), such as scannerless gating [35], [36], streak tube camera [20] etc. to achieve better range resolutions.

Table 1.2 lists selected research groups working on underwater range-gated imaging systems. This summary does not completely review the development of underwater range-gated imaging systems, but it aims to highlight some crucial achievements related to the motivations of this thesis.

Generally, the design and construction of range-gated imaging systems can scale from small hand held cameras to complex waterproof navigation systems. This involves various parties, such as naval research centres, national laboratories, private incorporations, and universities. Nowadays, the commercial products could be a

gigantic system surveying from above the water surface with LIDAR and scanning functionality, or featherweight intruder detection systems.

	System	Institution	Application	Working condition	Reference
1	SEE-RAY® & LRG in laboratory setup	NSWC and SPARTA Inc.	Underwater mine detection	Expected to operate up to 12m or 6.4 AL (attenuation length, see page 12)	[14][38]
2	LANL	LANL & SNL	Underwater and land based military targets	Tested up to 7m in turbid water condition	[40][41]
3	Laser viewing system	Japan Ministry of Transport	Underwater construction works	Tested up to 3m in turbid water condition	[42]
4	AquaLynx®	LaserOptronix	Underwater human viewing	Adjustable up to 100m viewing range	[43]
5	LUCIE	DREV	Underwater viewing system	Subjective evaluation of images with resolution targets	[44]
6	Range-gated UWLIS	NTU	Underwater viewing system	Expected to operate in industrial water areas. (Ports, oil rigs and etc)	[19]
Table 1.2 Selected research groups of range-gated imaging system in turbid underwater condition (1 attenuation length represents 1/C meter).					

Some researchers, such as: N. H. Witherspoon, J. H. Holloway [37], M. P. Strand [38], E. A. Mclean [39], B. A. Swartz [14], G. J. Yates [41] and others, have contributed substantially to the state-of-the-art of underwater range-gated technology. Numerous institutions, such as SPARTA Inc., Naval Surface Warfare Centre (NSWC), and Los Alamos National Laboratory (LANL), design their systems. The respective imaging models and experimental results have been established since the 1990s. Generally, they observed possible optimization of gate opening time and gate durations to achieve the highest image quality. These observations have subsequently motivated the analytical works presented in this thesis, such as the tail-gated imaging concept, analytical backscattering noise estimation, etc. (Further explanations are available in Section 1.3).

Yates et al. [41] from Los Alamos National Laboratory (LANL) and Sandia National Laboratory (SNL) evaluated the performance of range-gated imaging system in a surf zone area. Sakai et al. [42] used range-gated imaging system to monitor caisson positioning of underwater tunnel construction works. Their application is similar to this research project, which is aimed for short target distances in turbid medium. In the context of our application, there is a need to acquire clear near target images that are within the workspace of an URV manipulator. This is a range of less than 3 m for sub-sea inspection and repair missions. However, they did not focus on optimization issues, which could produce better image quality as reported in this thesis.

M. P. Strand [38] and Sakai et al. [42] have used a quantitative index to evaluate the range gated imaging system performance. However, this quantitative index used only a localized contrast value. It may not reflect the backscattering noise, which normally appears as uneven illumination and biased brightness levels. This has motivated the introduction of a global quantitative approach to assess the overall image quality more objectively. This approach has been related to the performance of range-gated imaging system comparatively.

AquaLynx[®] is produced by LaserOptronix [43]. The commercial range-gated imaging system is compactly sealed. At the current stage, the video presentations of range-gated images are still using standard frame-by-frame methods at a specific target range, rather than fusing individual gated image sequences together to provide a full depth of view scene. It may be a drawback for human viewing in multi-target or extended target conditions. Each gated image might not be able to show all targets within all ranges of a given scene or Field of View (FOV) even with larger or equal size Field of Illumination (FOI). Thus, the gated images might need to be range-gated incrementally or sequentially to cover all ranges with enhanced visibility. Naturally, it is possible to provide larger views to a human observer if each individual range-gated image could be fused to present better depth of field images. Prior to this fusion process, an image enhancement technique is crucial to eliminate the residual backscattering noise from the target feature itself.

For underwater imaging applications, various image-enhancement schemes have been used to further improve the range-gated images, such as image inversion, contrast enhancement etc. Meanwhile, there are more emerging image enhancement schemes available for underwater conditions, such as homomorphic filtering and adaptive

histogram equalization. It is thus believed that, the gated images could also be enhanced with those available methods. This has motivated the research to invoke and evaluate the performance of these emerging schemes for range-gated images specifically.

In order to fuse each enhanced image together, the fusion scheme should be able to discriminate the backscattering noise or non-target reflection from the gated target region. This has resulted in the last stage of optimization effort to fuse gated image sequences into video ready format for human visual application.

Basically, this project continues the work done by D. M. He [19], the system was setup with a water tank (3 m x 1 m x 1 m in size) attached to the camera input and laser output. In the initial stage, it was controlled by breadboard electronics and the images were captured using a Meteor II frame grabber [45]. In this thesis, further improvement over the system has shown higher system stability and better gate time control by using a delay generator [46]. The latest development by A. Sluzek[47] indicates better programming efficiency with Field Programmable Gate Arrays (FPGA) [48]. This system is currently set up in a laboratory condition. At this stage, it acts as the engineering test bed for upcoming deployment based on the future specific application needs.

Over the last few decades, research on the imaging system normally focused on hardware development, which aims either to enhance the target signal strength or improving the overall signal to noise ratio. F. M. Caimi [49] reported that a typical imaging system could be formed to produce tens of meters of visibility. It is primarily determined by the optical power, the detection means, the system geometry, and the optical attenuation of the medium. The system geometry and the optical attenuation of the medium are normally considered as working environments. Thus, it is natural for most researchers to concentrate on developing suitable system hardware for better visibility and efficiency. This will involve both optical power and the detection means.

For a typical range-gated imaging system, the optical power [50], [19] nowadays is commonly regarded as a blue-green pulsed laser, which suffers minimum absorption in water media. The detection means [50], [19] could be simply an intensifier gated still image, or video camera.

1.2.2 Laser

Most lasers used in underwater applications are either flash lamp pumped or diode pumped Nd:YAG (Neodymium-doped Yttrium Aluminum Garnet) lasers. Diode pumped solid-state lasers use less input power and have better compactness compared to flash lamp pumped systems [51]. The Nd:YAG laser is normally frequency doubled to 532 nm from 1064 nm wavelength. It is Q-switched to suit various power requirements ranging from a few tens mille-Joule (mJ) to a few hundreds mJ per pulse. On the highest extreme, McLean et al. [39] and Nebolsine et al. [52] used up to 1 Joule per pulse whereas Witherspoon et al. [37] and Grace et al. [31] used only less than 10 mJ per pulse of energy.

The eye safe requirement (maximum permissible exposure) is achievable with this energy range if it is diverged into wider angular subtense before the illumination takes place. Depending on the application, the diverging angle could spread the laser beam from a few mille-radians (mr) to 1 radian cone shape. Harsdorf et al. [21] has varied the field of illumination from 0.5 mr for focused detections applications, to 1 radian for sea floor scanning in his Remote Operated Vehicle (ROV) mission. For general imaging purposes, such as human viewing applications, the diverged beam system is found to have higher performance than spot beam system [53].

Pulse repetitive rate varies from application to application. It can be one pulse per second or train of pulses in kilo-Hertz (kHz). For non-water applications, range-gated imaging systems are normally equipped with a high repetition rate laser ranged up to 1 MHz as reported by Grace et al. [31]. For underwater imaging purposes, it ranges from a standard 10 Hz to 22 kHz [44].

One of the most influencing factors affecting the image quality is the pulse length. A good performance range-gated imaging system should possess as short a pulse as possible with adequate energy per pulse. Generally, it is set at nanosecond scale, such as from 0.5 ns to 20 ns. Some exceptions have been observed, such as George et al. [41] have used up to 20 picoseconds (ps) pulse length. Depending on the turbidity level, it is generally believed that a shorter pulse length would further enhance the system performance. The analytical work carried out in this thesis will explain this effect mathematically.

1.2.3 Camera

Most camera systems used are either Intensified Charge Coupled Devices (ICCD) or Intensified CMOS cameras. The intensifier is typically single or multi stage Multi-Channel Plate (MCP) with high gain and switchable circuit. Most of them are commercial products resourced from various advanced imaging bodies, such as ITT Industries, Hamamatsu, Photek, Kentech etc.

The CCD or CMOS arrays are normally designed specifically based on the application. It could be just a 2x2 pixel array for airborne LIDAR applications [24], [54], or 1534x1024 for scannerless gated imagers [35]. The Field Of View (FOV) of most cameras is adjustable with an optical zoom lens. The focusing of the lens can be set to infinity for turbid water condition. In this turbid environment, minor defocusing issues are negligible.

The gate time or duration should be short enough to reject the backscattering noise from the turbid medium with selective gate opening times. Most range-gated imaging systems deploy nanosecond gate duration, such as 5-500 ns from LUCIE2 [44] and 20 ns from Churnside et al. [23]. There are some exceptions, such as McLean et al. [39] and George et al. [41]. They have used as short a duration as 150 ps and 250 ps respectively. It is generally believed that the shorter the gate duration, the better image quality captured. Similar to the last section, the analytical work carried out in this thesis will explain this effect mathematically.

1.2.4 Applications

The first underwater range-gated imaging system was publicly reported by Christie et al. [29]. In terms of underwater visibility, it is normally not more than 100 m while the visibility for air could range to kilometres. Most of the systems are focused on short range, such as less than 10m for underwater viewing, and up to 60 m water depths for bathymetry surveys and mine detection.

For sub-sea working conditions, the water turbidity level could range from 0.1 to 2 /m attenuation coefficient. If it is calculated in terms of a medium-independent unit, the range-gated imaging system is expected to work from 6 to 8 attenuation length single way [14], [55].

This medium-independent unit, one attenuation length (AL), is defined as the reciprocal value of the attenuation coefficient ($1/C$, m) and it is correlated both to the

distance and to the turbidity of the medium. Though the laser pulse has travelled two times the target distance for an underwater active imaging system, the system achievement is normally calculated for single-way AL only. However, the performance achieved still depends on the system configurations and power. Compared to a normal light bulb imaging system, which could achieve visibility only up to 3 AL, the range-gated imaging system apparently is much superior.

1.2.5 The theoretical analysis of range-gated imaging system

In order to perform detailed analyses on the range-gated imaging system, various image transfer theories have been employed, such as optical transfer function, small angle scattering approximation etc. In this application, the Monte Carlo method is preferred because it is one of the general solutions for most stochastic models, such as backscattering noise. In terms of light propagation in turbid media, it could be used to simulate any air, water, tissue, and virtual environment. MCM assumes the light energy to be discrete photon particles or discrete energy packets interacting independently to each other except for the case of coherency. Generally, Monte Carlo simulation assumes that the photons can be traced in terms of path length, scattering directions etc., of each photon according to the nature of its own probabilities. The advantages and simplicity of MCM have made it a popular choice for researchers in various fields. This will be discussed in Chapter 2.

1.3 Objectives and Scope

The overall project work scope covers the development of an advanced underwater imaging system via two sequential stages, namely: a hardware upgrading and a system optimization stage that is specifically dedicated to sub-sea inspection and repair applications.

In the first stage, the system specifications such as laser power, imaging technique, and camera sensitivity are determined. This has basically been addressed and defined by He et al. [19] with additional hardware improvement in this project. For the system optimization stage, it is required to further fine-tune and enhance the image quality based on existing hardware and imaging setup.

At the current stage, the research focuses on the development of both real time and offline video delivery for a human operator to manoeuvre dexterous URV or to perform a manipulator task over a short distance (less than 3 meters) in a highly turbid

seawater environment [20]. The objective of this research project is to analyze and optimize an existing range-gated imaging system (laboratory setup), specifically for near targets in a turbid water environment. The near target condition is defined by the pulse length and working condition. The project:

- 1) Investigates the backscattering phenomenon within the Reflected Image Temporal Profile (RITP) analytically and numerically as a function of pulse length, gate timing, and opaque target effect. RITP is a newly defined term in this research to describe the irradiance reflected from both the scattering medium and an underwater target. Subsequently, this thesis proposes a mathematical formulation for the temporal response of range gating physics as Signal to Backscattering Noise Ratio (SBR). This has contributed to a correction of the backscattering effect within the RITP with opaque target effect.
- 2) Documents further enhancement of the gated image acquisition by the tail-RITP gating concept theoretically and empirically.
- 3) Performs image enhancement and image fusion analysis of gated images for human visual application in near target turbid seawater conditions. Hence, this thesis proposes a novel fusion framework for gated images in multi-target or extended target condition.
- 4) Evaluates the performance of this system globally and quantitatively by correlating the output image quality in laboratory conditions.

The theoretical analysis focuses on backscattering noise of a range-gated imaging system from a turbid environment, both temporally and spatially. Based on this analysis and the experimental results, this thesis evaluates the residual backscattering noise that is still visible in range-gated images. Thus, it aims to investigate the performance of the range-gated imaging system and its possible optimization by minimizing its residual backscattering noise from near target turbid medium.

It is well known that shorter pulse length and shorter camera gate duration will enhance the range-gated image quality. This effect is shown experimentally and qualitatively in other range-gated imaging applications. However, there is no existing analytical approach or formulation describing the backscattering noise as a function of outgoing pulse length and gate timing with opaque target effect. This thesis evaluates

the variation of backscattering noise within the target irradiance pulse (actual Reflected Image Temporal Profile, RITP) and its effects on the Signal to Backscattering Noise Ratio (SBR) and the image quality. This analysis provides correction of backscattering noise with the RITP by using a modified formulation adopted from the simple LIDAR equation. Besides the sensor effect, this phenomenon has also contributed in the improvement of gated image quality for shorter pulse length and shorter gate duration effect.

In order to further verify this theory, knowledge of ocean optics is crucial to determine the light propagation characteristics. This involves various solutions of radiative transfer equations for seawater conditions. Since the variation of backscattering noise cannot be accurately predicted by an empirical or analytical approach due to its complex radiative transfer geometry, the Monte Carlo method is used to simulate the stochastic nature of photon particles propagating in a homogeneous turbid medium. The simulation model is verified using Yaroslavsky's model and experimental results within 20% relative errors. Under near target turbid conditions, the simulation shows that tail RITP gated images are better than front RITP gated images. This agrees well with the theoretical model and Witherspoon's observations from their range-gated imaging system.

Most range-gated imaging systems were not evaluated objectively. They were normally compared to non-gated imaging systems by using subjective or localized contrast calculations. This has made the optimization work difficult without sensitive and objective performance indexes to quantify the system output. Thus, it is necessary to establish a standard evaluation method to determine the performance of the range-gated imaging system prior to the optimization stage.

A quantitative index is suggested in laboratory conditions to compare the quality of turbid water images to a clear water reference image. In this case, the quantitative index is correlated to the actual system performance.

For turbid water imagery, this approach basically assumes that a given imaging system capable of minimizing the scattering noise should produce images close to their reference in non-scattering or clear water conditions. Thus, this thesis compares gated and non-gated imaging systems in increased turbidity more objectively. These comparisons are used as the performance index or reference to fine-tune the system

parameters. The same measure will also be used to verify the tail RITP gating technique, as suggested by the theoretical model and Witherspoon's [37] observations from their range-gated imaging system.

The next optimization steps involve post processing of range-gated images to further enhance the gated images and to deliver composed image sequences for human visual applications. This is initiated with a preliminary analysis of a novel fusion framework for range-gated images in multi-target or extended target conditions. This includes both image enhancement and fusion schemes for this specific application.

There are various emerging techniques in image enhancement schemes available for underwater conditions, such as homomorphic filtering, adaptive histogram equalization, etc. Basically, they address the scattering noise issue of underwater images. A similar appearance of scattering noise has also been observed in range-gated images. Thus, it is believed that, the gated images could also be enhanced with these available methods. This has motivated the research to use those emerging enhancement schemes for the specific needs.

In the later phase of this fusion framework, the research concentrates on the drawback for human viewing purposes in multi-target or extended target conditions. This thesis demonstrates possible enhancement of viewing capability if individual range-gated images are fused together to achieve depth of field. This has motivated the preliminary investigation to fuse incrementally or sequentially gated images into video ready format for human visual application.

1.4 Organization of the thesis

The organization of this thesis corresponds to the research methodology taken for this project. Thus, it is crucial to understand the research approach before looking into the research work and the thesis. General research methodology concentrates on the literature reviews, theoretical analysis, experimentation, and documentation of research results.

1.4.1 General research approach

Figure 1.3 illustrates the research methodology layout of this project. The research objective is to enhance or optimize the performance of existing range-gated imaging hardware. The images must fulfil certain requirements. It should be possible to

produce high resolution video or continuous frames for human visual applications in turbid water conditions.

The project is planned in a few milestones objectives. First, the academic problem is identified. It was common to assume that the laser pulse length effect and the backscattering noise are basically negligible in a range-gated imaging system. However, various observations from the empirical studies show the backscattering noise is still visible even though the image quality has been much improved compared to normal non-gated images.

Hence, the research aims to model the variation of backscattering noise within the actual Reflected Image Temporal Profile (RITP) as a function of pulse length and gate timing.

The second milestone involves temporal analysis of backscattering noise within the actual Reflected Image Temporal Profile (RITP). It has subsequently affected the Signal to Backscattering Noise Ratio (SBR) and the image quality. This phenomenon

is used to explain mathematically why shorter pulse lengths and gate durations are better for range-gated imaging systems. This theory is also simulated numerically.

The last two milestones compose a fusion framework for gated images in multi-target or extended target issues. It proceeds with a spatial analysis of the backscattering noise effect in gated images. It shows that most backscattering noise appears to be non-uniform illumination or brightness levels in the underwater images. This has motivated the use of some emerging techniques to restore the uneven effect. This research milestone concentrates on some selected methods to improve this residual backscattering effect from range-gated images specifically.

The final milestone attempts to fuse the image sequences together to form a full depth of field video.

Besides, this project has also set up a standard evaluation method particularly for this optimization process. An image quality index is taken as the evaluation metric to justify the research results together with the subjective evaluation from naked eye observations.

1.4.2 Thesis outline

Since the application is in seawater condition, knowledge of ocean optics is crucial to determine the light propagation characteristics. General inherent optical properties, underwater visibility, and underwater image quality measures are reviewed. These have resulted in various solutions of radiative transfer equations for seawater conditions. Among them, the Monte Carlo method is a preferred and a general review is also presented. Based on those principles of ocean optics, Chapter 2 gives an overview of range-gated imaging theory. It reviews some of the popular imaging models for a range-gated imaging system (in the spatial frequency domain), as well as a short review of the most relevant LIDAR equations as functions of pulse length and transmitted pulse profile.

Chapter 3 focuses on the introduction of Reflected Image Temporal Profile (RITP). In order to examine the diverged beam propagation in a complex geometry, the Henyey Greentain phase function is adopted in the Monte Carlo simulation. The simulation model is then verified with Yaroslavsky's model and by experimental results.

Chapter 4 depicts the hardware setup of the range-gated imaging system in a laboratory condition together with the timing diagrams in nanosecond scales. This is

followed by a preliminary analysis of each component in the system to enable better equipment selection and design work in actual prototype developments. By simulating turbid water conditions with Mylanta®, the gated and non-gated imaging systems are compared to evaluate the performance of the current range-gated imaging system. The output image quality is correlated to the actual performance of the system with quantitative scales. The Modified Fidelity (MF) index shows its adequacy for this purpose.

Chapter 5 reports the analytical work of backscattering noise for a range-gated imaging system in the time domain. The variation of this noise effect has affected the Signal to Backscattering Noise Ratio (SBR). This analytical formulation explains the feasibility of the tail gating concept. Further analysis clarifies how shorter pulse lengths and gate times can improve the range-gated image quality from the perspective of backscattering noise effect within the actual RITP mathematically.

Chapter 6 reports a preliminary analysis of the fusion framework for range-gated images. While RITP analysis in the previous chapter focuses on single-pulse-single-target conditions, multiple targets or extended target issues could be considered as multiple complex RITP arriving on every pixel of a gated image. This has motivated the research to fuse the images together to form a complete FOV with larger depth of view. In this preliminary analysis stage, a simple technique is found effective to fuse incremental or sequential range images together. This image fusion framework is a combination of both an image enhancement and a fusion scheme to integrate the enhanced portions of multiple targets or extended target images.

In Chapter 7, the main contributions are summarized first, and then the future research directions are outlined.

CHAPTER 2

LITERATURE REVIEW

Since the prospective applications of NTU range-gated imaging systems are in seawater conditions, knowledge of ocean optics is crucial to determine the light propagation characteristics. General inherent optical properties, underwater visibility and underwater image quality measures are reviewed. In the literature, the analysis of ocean optics and image transfer in turbid media has resulted in various solutions of radiative transfer equations for seawater conditions. Among them, the Monte Carlo method is a preferred approach to simulate the light propagation in a complex geometry with the least assumptions made. Thus, a general review of the Monte Carlo algorithm is also presented. Based on various principles of ocean optics, this chapter gives an overview of range-gated imaging theory. It reviews the most popular imaging models for range-gated imaging system (in the spatial frequency domain), as well as providing a short review of most related LIDAR equations as functions of pulse length and transmitted pulse profile.

2.1 Oceanography

Optical oceanography is the root of underwater optical imaging system development. It considers the sea from an optical standpoint and is generally considered as a special branch of oceanography [56]. The theoretical approach to explain the light field propagation or underwater imaging phenomenon relies on the theories of ocean optics, it is essential because of the complexity of the scattering phase function and the randomness of optical properties in natural water. The exact solution of light field propagation in underwater conditions is not possible currently. It is normally suggested to approximate the light field distribution with some experimental and analytical results. Among those popular approaches, Monte-Carlo simulation has yielded reliable results in various situations [57].

The introduction of photoelectric cells [56] in 1922 and photo-multiplier tubes in 1955 for marine observations has revolutionized the optical techniques. Another strong impetus has been provided by the invention of the laser, which is turning out to be an effective tool in oceanographic optics.

Today, the bulk or large-scale optical properties of water are conveniently divided into two mutually exclusive classes: inherent and apparent. Inherent optical properties (IOP) are those properties that depend only upon the medium, and therefore are independent of the ambient light field within the medium. The fundamental IOPs are the absorption coefficient, the volume scattering function, the index of refraction, the total attenuation coefficient (C), the scattering phase function, the single scattering albedo (the ratio of scattering coefficient over total attenuation coefficient), etc. Apparent optical properties (AOPs) are those properties that depend both on the medium (the IOPs) and on the geometrical (directional) structure of the ambient light field. It has long been known that the total radiant energy from the sun and sky loses half of its value in the first half meter of water, owing chiefly to strong absorption in the infrared wavelength. This phenomenon is subsequently expressed in the radiative transfer function of the sea, which provides the connection between the IOPs and the AOPs.

The core problems of the investigation of the optical properties of oceanic waters, in conjunction with their suspended (particles) and dissolved (molecules) constituent substances, are the scattering and attenuation effects to electromagnetic wave propagations. The physics of both effects are crucial to basic mathematical establishments of underwater imagery. Hence, it is appropriate to study the actual physical events for both effects in order to establish the mathematical models of underwater imaging system.

Details of mathematical derivations and definitions of these optical properties are available in various textbooks [56], [57] and Appendix A. The following sections aim to highlight some historical and updated studies on the basics of ocean optics only. These optical properties have been tightly linked to the underwater visibility/image quality issues throughout this thesis. From the academic point of view, the range-gated imaging system is in fact an agent to discriminate the unwanted noises from desired signals and thus enhancing the underwater visibility/image quality.

2.1.1 Scattering

Scattering, together with absorption, is the fundamental process, which determines the propagation of light in seawater. It could be produced by the water itself, dissolved materials, or suspended particles. The total scattering co-efficient (B) and Volume

Scattering Function, (*VSF*) have been deduced to enable an investigation and prediction of scattering effect. The volume scattering function derives the differential scattering cross section per unit angular volume out of the light travelling axis. The integration of the scattering function from zero to π gives the total scattering coefficient (*B*).

Scattering by pure water is often considered as a problem of molecular scattering. Rayleigh theory in 1871 and Fluctuation theory in 1908-1910 [55] were introduced to describe the scattering by liquids. In Rayleigh theory, where the particle size is much less than the wavelength, only elastic scattering is considered.

Scattering through particles may be looked upon as the result of three physical phenomena when a finite photon interacts with a particle in the water medium, namely: diffraction, refraction, and reflection externally [58]. Besides the general mechanics of discrete photons in a homogenous medium, wavelength selectivity of scattering by seawater also arises from the following three agencies in the medium, such as: scattering by the water itself, scattering by small sized particles, and absorption by particles.

There are three well-known methods [59] to handle the problem of light interactions with irregularly shaped particles, namely: approximation with spherical diameters of particles, averaging the optical characteristics of each particle, and representing the elementary volume of a scattering medium with a single 'average' particle. The latter is among the most popular approaches to model the statistical properties of an ensemble of irregularly shaped particles. With particle sizes larger than wavelength, Mie scattering calculations [56] and van de Hulst [59] (for soft particles) are able to approximate the observed volume scattering functions, except at very small angles, given the proper particle optical properties and size distribution in elementary volumes.

However, the actual *VSFs* are generally affected by particles (which is always present and unpredictable). Hence, it is more reliable to determine the scattering properties of natural waters by measuring the water itself. The most carefully made and widely cited scattering measurements were carried out by Petzold [56] in 1972. The measurements are stated in normalized volume scattering function format, or scattering phase function (β). One of the latest natural water phase functions was

measured by Victor et al. [60] in 2002. They reported various measured scattering phase functions of natural waters across various ocean, lake and river locations around the globe. Theoretically, the Henyey-Greentein phase function is mostly adopted to approximate the actual phase functions for seawater conditions. More detailed phase functions analysis is available in Section 2.3.5 and Chapter 3.

For scattering coefficients, various efforts have been carried out for measurement in various locations of sea or ocean, such as: Scottish coastal water [61], Ryukyu Islands water [62], North Pacific Ocean [63], etc. Natural seawater could achieve as high as 1.8/m of scattering coefficient with single scattering albedo at 0.83 [20]. Thus, it becomes critical for underwater imaging systems to achieve good image quality and visibility in this condition. The needs for an advanced imaging system are even higher when it has to deal with industrial water, or silky water area.

2.1.2 Absorption

It is generally thought that Clarke et al. [55] in 1939 have been relatively successful in emulating pure water and seawater. Their attenuation of visible wavelength is considered representative. The light attenuation of both water types shows little differences. Light absorption in these waters show minimum absorption around 450-550 nm wavelengths. These results are similar to measurements from other researchers, namely Zoloratev and Demin in 1977 [64], Hale and Query in 1973 [66], Jackson in 1975 [66], Smith and Baker in 1981 [67], etc.

Research has shown that absorption by particles in seawater tends to increase towards shorter wavelengths. Kalle [57] in 1962-1966 summarized the complex mixture of compounds found in seawaters as “yellow substance”. It is formed from carbohydrates by a “Maillard” reaction. The formation is stimulated by heat; alkalise reaction and the presence of amino acids, and leads to end products of yellow or brown melanoidines. Bricaud [57] in 1981 gave the absorption coefficient in 440 nm wavelength due to yellow substance for selected water, but because of the variability in yellow matter concentrations, no model yet exists that allows for the direct determination of a general absorption coefficient of all wavelengths for a given concentration of yellow substance.

Both scattering (B) and absorption coefficients (a) would be added up to form total the attenuation coefficient, C .

2.1.3 Underwater Visibility

The main objective of this project is to further enhance the gated images and visibility in turbid water condition. Thus, the evaluation part of this research process tends to be critical when the system approaches its fine-tuning stage. Unfortunately, there is no standard reference to define a quantitative method to measure the overall image quality. Nowadays, most of the system performance evaluations are focused on the efficiency, signal to noise ratio, subjective evaluations or scene modulation (contrast) calculations.

The “underwater visibility” is one of the performance indexes that have not been used extensively in underwater imagery evaluations. This index is perceived as an alternative to image quality indexes, which is suitable in evaluating underwater optical detection systems if clear image quality is not available or required. In this case, the visibility indicates the maximum distance or turbidity level achievable by a given imaging system in a predefined target-system configuration.

P. Bouger described the simplest method of estimating the transmittance of seawater (or visibility) from the depth of White Sea bottom as early as the beginning of the 18th century. Only in 1865, Secchi and Cialdi systematically used white and coloured discs to estimate the transmittance of the waters of the Mediterranean [68]. These observations were gradually standardized for seawater optical properties evaluation. Mathematically, K. S. Shifirin [68], Haltrin [69], Keen et al. [70], and Zaneveld [71] have formulated the Secchi disk depth or maximum detectable distance as a function of the total attenuation coefficient, target reflectivity, and background reflectivity. However, there is still minimal connection between these standard observations (equivalent Secchi disc depth) and a given imaging system performance.

Some effort was made to characterize the performance of underwater imagery as a function of water characteristics. Pollio et al. [72] described it as Visibility Evaluation of Underwater Systems (VEUS). They observed at least nineteen variables should be introduced into a mathematical model of an underwater photographic system. In their model, they proposed area-weighted averages of both total exposure and scene modulation (contrast value) of bottom target and background reflectance. This index is advantageous to evaluate the extent of a given imaging system, which is defined as 2% of the scene modulation for maximum range or turbidity. Unfortunately, there is

still a lack of theoretical basis to select proper weighting coefficients to compensate uneven scattering noise or illumination of an image.

2.1.4 Image quality evaluations

As stated by J. D. Howe in 1993 [72], accurate predictions/measurements of an imaging system performance are important for several reasons. The predictions or measurements serve as a guide for system development by providing a means for comparing systems in their design phase, and they can be used to decide if systems with a specific design will meet established requirements. One of the earliest comprehensive performance evaluations for underwater imaging systems, was carried out by Hodara et al. [73] in early 70's. They derived the Performance Comparison Figure (PCF) that is proportional to the signal to noise ratio one expects to see at the detector with a given type of source and a given electrical power input. As such, the PCF serves as a numerical indicator of the efficiency of the underwater imaging system. This indicates a standardized comparison for system efficiency between different underwater imaging systems in 1973.

In this thesis, the output image quality is the major concern instead of system efficiency. In laboratory conditions, this research aims to maximize the image quality within the existing hardware configurations. Thus, it is generally assumed that the image quality is correlated positively to the overall performance of this specific system. By measuring or quantifying the image quality, the system performance could be evaluated accordingly.

For underwater range-gated imaging system, it was claimed the target distance detected could be up to 6 times [34] longer than for normal bulb lamp illumination. However, this subjective observation does not correlate quantitatively to the enhancement of images. Thus, it is needed to assess the image quality more objectively than naked eye observations, or to quantify the image quality.

Various approaches have been done to evaluate the underwater image quality (qualitatively or quantitatively) to represent the imaging system performance, but the effort was not effective enough to establish a recognized standard or benchmark which would satisfy the specified needs in imaging system optimization processes.

Qualitatively, Harsdorf et al. [50] compared subjectively range-gated and non-gated images at 10m target distance. It was shown that the range-gated image is good, while

normal light-illumination system image was blank. He et al. [19] and McLean et al. [39] have claimed the range-gated imaging system is better than a normal active imaging system, but the improvement was not reflected objectively.

Chu et al. [75] have used two methods to assess the image quality of an underwater imaging system. They used the Difference Histogram Threshold (DHT) and Weighted Average of Power Spectrum (WAPS) to assess image quality quantitatively. The results were feedback to the system to control the lighting power and distance to target. However, the images produced by this method were highly affected by the scattering effect. It is because the methods used are not capable of differentiating the actual target image contrast from scattering noise. Witherspoon et al. [37] show the Modulation Transfer Function (*MTF*) of the images is generally related to the scattering effects. They observed some linearity of image quality in terms of *MTF* and turbidity level of a water medium. M. P. Strand [38] and Sakai et al. [42] used a localized contrast calculation of standard underwater target image to evaluate the range gated system performance. However, the localized index may require subjective judgment to choose an “appropriate” point to evaluate the whole set of images in increased turbidity. If the computational point is not chosen properly based on subjective measures, it may not reflect the overall uneven illumination and underwater scattering effects for a complete or fused image objectively. Thus, a quantitative and global index of assessing image quality is necessary.

The image quality can be measured in different ways [76], such as statistical, incorporating *MTF*, multidimensional impairment, etc. The image quality evaluations can be pursued from a few fundamentals ways. Visuo-recognitive processing is not an isolated process but instead should be considered as an essential stage in human interaction with the environment. Thus, the quality of an image is regarded not in terms of the distortions in this image but instead in terms of adequacy of this image as input to the vision stage of the interaction process. The techniques to examine the adequacy can be expressed in terms of linearity, signal to noise ratio, temporal variability, spatial variability, inter-device variability, uniformity, *MTF*, spectral colorimetric characterization, broadband colorimetric characterization, colour gamut etc. In order to specifically improve or fine-tune the system to achieve highest image quality in laboratory conditions, Tan et al. [10] proposed a global image quality metrics together with the testing procedure to measure the output image quality in

laboratory conditions. This approach is adopted into this thesis for the evaluations purpose.

2.2 Time-dependent Radiative Transfer Equations (RTE)

It is generally believed that the light scattering in a scattering medium is the major factor in deteriorating the image quality. In order to attain better image quality or visibility, it is crucial to express the interaction of light with the medium (e.g. seawater) analytically. The interaction of light with disperse systems could be analyzed with two popular approaches, namely: Maxwell's equations and Radiative Transfer Equations (RTE) [77]. The radiative transfer or transport theory replaces the disperse system with a continuous medium with some constant phenomenological propagation parameters. This approach is frequently considered as a specialized branch of mathematical physics with its unique methods and techniques.

While Maxwell's equations can be used only for small numbers of particles mainly because of limits imposed by modern computers [59] (exception found in Preisendorfer's works [78], he manages to form the RTE with Maxwell's equations).

For radiation in underwater conditions, Mobley [57] derived the most general form of the radiative transfer equation. It governs the time-dependent and three dimensional behaviour of the radiance $I(\vec{x};t;\xi;\lambda)$ [$\text{Wm}^{-3}\text{sr}^{-1}\text{nm}^{-1}$], including the effects of inelastic scattering and internal sources as:

$$\frac{1}{v} \frac{\partial}{\partial t} (I) + \xi \cdot \nabla (I) = -C \cdot I + I^E + I^I + I^S \quad (2.1)$$

where $v=v(\vec{x};t;\lambda)$ is the speed of light in the medium at position $\vec{x}$, wavelength λ and time t . ξ is equal to $\vec{v}/|v|$, the directional unit vector. C is the beam attenuation coefficient of the elementary volume. I^E and I^I represent the bi-static elastic scattering and inelastic scattering respectively, and the only true emission term, I^S is normally predefined as one of the boundary conditions.

For pulsed light sources, the non-stationary transfer equation possesses two bi-static scattering terms from its surrounding homogeneous volume, which could be an elastic or an inelastic case. If the inelastic scattering term is negligible [79] and the time factor of elastic scattering is translationally invariant [80], the radiance $I^E(\vec{x};t;\xi)$ of elastic scattering term could be described as:

$$I^E = \frac{B}{4\pi C} \iint_{4\pi} I(\vec{x}; t; \xi) \beta(\xi; \xi') d\xi' \quad (2.2)$$

where B is the total scattering coefficient for the elementary volume, β represents the phase function characterize the scattering from ξ to ξ' . ξ' is the unit directional vector out of the unit volume.

Basically, the non-stationary light scattering problem consists of determining the medium response $I_\delta(\vec{x}; t; \xi)$ to an instantaneous excitation. For a source function $I_0(t)$, the radiance may be found by integration,

$$I(\vec{x}; t; \xi) = \int_0^t I_\delta(\vec{x}; t; t') I_0(t - t') dt' \quad (2.3)$$

$I_\delta(\vec{x}; t; \xi)$ is named differently by various research disciplines, such as the Green's function of the non-stationary transfer equation, temporal point spread function, photon time-of-flight fluctuations, or the photon path distribution function [79].

Generally, there are numerous techniques to solve Equations 2.1–2.3 analytically and numerically, such as discrete ordinate [81], invariant imbedding [82], Monte Carlo method [57], [83], finite element analysis [84], diffusion approximations [79], [85], etc. The diffusion approximations are used to derive various forms of diffusion equations. It is preferable for simple geometrical conditions and larger scattering lengths. For basic LIDAR analysis, diffusion equations yield a better understanding in the close form solution. However, most of the underwater imaging applications may not be predictable with analytical equations because of the complex geometrical condition, such as diverged beam propagation with complex target reflection. Thus, numerical approaches are normally taken to simulate the light propagation in underwater fields, such as statistical (Monte Carlo), deterministic (Finite Element Analysis) methods, etc. Among them, the Monte Carlo Method (MCM) is preferable with advantages of least assumptions made and its robustness to any geometrical condition. A key advantage [86] of Monte Carlo approaches is that virtually any environment can be modelled accurately. With deterministic algorithms (Finite Element Analysis), there are often severe restrictions on the allowable geometry and materials. For this reason, the following sections aim to review the algorithms of the Monte Carlo method and its state of the art.

2.3 The Monte Carlo Method

The Monte Carlo Method (MCM) refers to a technique first proposed by Metropolis and Ulam [87]. It is one of the general solutions for most stochastic models, such as neutron propagation and electron scattering. In terms of light propagation in turbid media, it could be used to simulate any air, water, tissue, and virtual environment. MCM assumes the light energy as discrete photon particles or discrete energy packets interact independently to each other except for the case of coherency. Generally, Monte Carlo simulation [57] assumes that the photons can be traced in terms of path length, scattering directions, etc, of each photon according to the nature of its own probabilities.

The advantages and simplicity of MCM have made it a popular choice for researchers in various fields. In medical radiation physics, Buvat et al. [88] found over thousand MCM related papers from 1970 to 2000. For light propagation in turbid media, it is quite difficult to obtain precise descriptions of the features and performance of specific MCM codes without going into detail through the publications or software user manuals respectively. Thus, it was suggested to standardize the general framework and verifications procedure of MCM, to enable the selections and comparisons of various MCM implementations. Unfortunately, despite various categorizations to describe MCM implementations, there is no effort leading to this direction (standardize the general framework) so far. Thus, this thesis initiates an effort to organize the features of each MCM code in a diagram form to enable better comparisons among them.

Monte Carlo simulations can be categorized under numerous criteria. They could be simply categorized into fixed and variable step size systems [89]. This approach is adopted with review of MCM literature.

At the component level, Tinet et al. [90] outlined two major processes for Monte Carlo estimators, namely Information Generator (IG) and Information Processor (IP). IG aims to generate photon propagation with a predefined photon source and geometrical conditions, while IP retrieves desired measurements from IG processes. Curtis et al. [57] perceived the MCM must contain simultaneous measurement of the inherent optical properties of the seawater, environmental parameters, and radiometric quantities. G. Zaccanti [91] highlighted the MCM capability to deal with different

situations regarding source-receiver characteristics, boundary of the medium and scattering characteristics of the medium. In terms of the MCM process flow, Govaert et al. [92] emphasized on four main steps, namely: generation of the rays, localization of the ray object intersection, determination of the type of interaction and scattering direction, and extraction of relevant information from the ray paths.

Based on their observations, it is proposed to characterize a typical Monte Carlo simulation of light propagation in turbid media into a general framework. Figure 2.1 depicts those general features of the Monte Carlo simulations as a diagram to characterize the numerical approaches in complex geometrical conditions. This framework will be used to aid the review of MCM and as the groundwork of the Monte Carlo algorithm in Chapter 3. This pictorial description potentially serves to standardize the general framework and verifications procedure of MCM, and is expected to aid in the selections and comparisons of various MCM implementations.

From Figure 2.1, the MCM algorithm takes all predefined inputs, such as boundaries and target properties, Inherent Optical Properties (IOP) of the medium, and light sources. Each of them will be reviewed separately in the later sections. The core algorithm to compute light paths for each individual photon is done in the Information Generator (IG). This includes various variance reduction schemes to improve the computation efficiency and accuracy. Every step of a photon's propagation will be

checked against a set of boundaries and survival criteria. The Information Processor (IP) will handle those photons accumulated over a preset receiver area and FOV. The results will be converted to the required measurement units or lead to photons categorizations.

In the following sections, a variable steps MCM is introduced as the basis of this algorithm. Each sub-category in Figure 2.1 will be further reviewed. The key parameters from each sub-category that will affect the simulation results are highlighted.

2.3.1 Introduction of variable step sizes Monte Carlo algorithm

First, it is assumed that the water medium is homogenous and that the light consists of photon particles with a specific wavelength. With a given photon at point $\vec{x}$, the photon travels in direction ξ before it encounters a water molecule or other particle. Without any scattering event as well as the external source, the distance travelled by the photon until it hits another molecule can be derived from Equation 2.1 as:

$$\frac{\partial}{\partial l}(I) = -CI \quad (2.4)$$

∂l denotes the delta distance travelled by a photon before it encounters a scattering or absorption event. It could be easily characterized as a mean free path of photons/light intensity in bulk volume. Thus, integration of intensity I from its original value I_0 , achieves distance l :

$$I = I_0 e^{-Cl} \quad (2.5)$$

Let's assume the optical path length, $\tau = Cl$. The reduction in radiance can be explained in terms of the fate of individual photons if the probability of any particular photon being absorbed or scattered out of the beam between optical path lengths τ and $\tau + \partial\tau$ is

$$p(\tau)d\tau = e^{-\tau}d\tau \quad (2.6)$$

Note that this function $p(\tau)$ satisfies

$$\int_0^{\infty} p(\tau)d\tau = 1 \quad (2.7)$$

i.e. it is a probability density function (pdf). The probability that a photon is absorbed or scattered somewhere between $\tau = 0$ and τ is given by the cumulative distribution function $P(\tau)$:

$$P(\tau) = \int_0^{\tau} p(\tau') d\tau' = 1 - e^{-\tau} \quad (2.8)$$

Let K be a random number drawn from the unit interval $<0, 1>$. The distribution of K is uniform on $<0, 1>$ interval. The associated pdf of K is given by

$$p(K) = \begin{cases} 1 & \text{if } 0 \leq K \leq 1 \\ 0 & \text{if } K < 0 \text{ or } K > 1 \end{cases} \quad (2.9)$$

The fundamental principle of Monte Carlo simulation is the equation $K=P(\tau)$ uniquely determines τ in such a manner that τ falls in the interval τ to $\tau + d\tau$ with frequency $p(\tau) d\tau$. This result is completely general.

Therefore

$$K = P(\tau) = 1 - e^{-\tau} \quad (2.10)$$

Gives

$$\tau = \ln(1 - K) \quad (2.10a)$$

Equation 2.10a is then used to randomly determine the optical path length τ travelled by a photon between one scattering or absorption event and another.

Subsequently, the interaction between the photons and the medium is either an absorption or a scattering event. This is decided by drawing another random number K from $<0,1>$ and comparing it with the albedo of single scattering, $A = B/C$. If $K > A$, we let the interaction be an absorption event; if $K \leq A$, the interaction results in scattering. The use of A makes clear why it is sometimes called the probability of photon survival. If it is a scattering event, the new photon direction can be randomly determined by use of the phase function $\beta(\psi)$. In this case, ψ is referred to as the new angle generated out from its previous reference or event.

Assuming the azimuthal angle (ϕ) and scattering angle out of ξ axis (ψ) are independent to each other, the pdf can be written as a product of pdf's for ϕ and ψ :

$$\beta(\psi) \sin \psi d\psi d\varphi = p_{\psi}(\psi) d\psi p_{\varphi}(\varphi) d\varphi \quad (2.11)$$

The azimuthal angle φ (which determines the plane of the scattering event relative to the reference direction) is uniformly distributed on the interval from 0 to 2π . Thus,

$$p_{\varphi}(\varphi) d\varphi = (1/2\pi) d\varphi \quad (2.12)$$

and

$$p_{\psi}(\psi) = 2\pi\beta(\psi) \sin \psi \quad (2.12a)$$

In order to determine the scattering angle ψ , we draw a random number K' from the uniform distribution on $<0, 1>$ and set

$$K' = P_{\psi}(\psi) = \int_0^{\psi} p_{\psi}(\psi') d\psi' = 2\pi \int_0^{\psi} \beta(\psi') \sin \psi' d\psi' \quad (2.13)$$

Because of the complicated shape of $\beta(\psi, r)$, Equation 2.13 must generally be solved numerically in order to determine the value of ψ corresponding to K' . The same type of analysis applied to φ yields

$$\varphi = 2\pi K'' \quad (2.13a)$$

where K'' is yet another random number drawn from the uniform distribution on 0 to 1.

Even though many photons are traced, a solution of the radiative transfer equation is built up with one photon at a time. Internal sources can be included in the radiative transfer equation by generating photons at the desired locations within the water. It is possible to solve the radiative transfer equation in terms of optical depth z regardless of the spatial in-homogeneities in the actual water body, where the in-homogeneities can be modelled in world coordinate system as the boundary conditions.

2.3.2 Information generator - photons propagation

From the previous section, there are basically three random numbers generated to characterize a complete photon movement. This is just the basic step of Monte Carlo algorithm without any source and boundary conditions. In practice, a complete run of MCM should be able to predict light propagation and its behaviour at limited and complex geometrical conditions. Figure 2.2 illustrates a variable-step Monte Carlo

algorithm with predefined source distribution and boundary conditions. The variable and fixed step sizes MCM are different in their determination of photon movement. The former calculates every photon dislocation by using Equations 2.10 and 2.10a, whereas the latter normally fixes every step size by constant time duration. In Figure 2.2, the grey lines represent the core algorithm described in Section 2.3.1. It is the most time consuming routine in a complete MCM run. Thus, most computation enhancement schemes introduced aim to enhance the efficiency within this routine.

For complex geometrical boundary conditions, the routine will always check the photon positions against boundary limits. If the photon has proceeded out of the medium, it has to be absorbed, transmitted, or reflected. The probability of a reflection event is determined by using Fresnel's law. A successful reflection will return the photon back to the medium at a reflected angle, while transmitted photons will be updated to another routine or neglected.

In terms of propagation mechanics, most MCMs are run in specific coordinate systems, such as Cartesian or polar system. The detailed descriptions of propagation mechanics are available in the literatures [89], [93] and Appendix B.

The most common optimization schemes [88] deployed to enhance the system efficiency are:

- 1) Analytical models to hybrid into the simulation models,
- 2) Approximation based on geometrical considerations,
- 3) Variance reduction techniques,
- 4) Parallelization techniques.

Variance reduction schemes have been proposed to reduce the computation time and enhance the system efficiency [94], [95], [96]. The most common and simplest variance reduction scheme is assigning a weight to each photon at its initiation. After each propagation step, the photon's weight is reduced by the probability of absorption. Usually, a photon is completely absorbed based on the absorption probability when the weight falls below a predefined threshold level. Thus, this implicit capturing technique provides some absorption information at each photon step, rather than just at times when the photon is completely absorbed.

2.3.3 Input - photon generations (source)

Most photon initializations require only a point source or pencil beam with the same direction for a complete MCM run. This feature is justified if the light source size is negligible. Alternatively, the distribution of the actual light source within the target medium should be considered if the size of the source is significant. The distribution of the light source varies from application to application. As an example, Maiorova et al. [97] initialized the photon in diverged angle to simulate diverged laser beam propagation in their virtual tissue phantom.

For a continuous light source, the output power profile is not critical unless it is a modulated signal, such as attempts done by Testorf et al. [98]. Each complete run is just a summation of routines for numerous photons (ranging from 1000 [98] to 4.3×10^{17} [39]). The number of photons is chosen to compromise computation times and computation errors. The increased number of photons per MCM run will increase the computation time but reduce the statistical and quantization errors. On the other hand, fewer photons per run will increase the errors but reduce the computation time. This has been well discussed by Testorf et al. [98].

For pulsed light source, the initial pulse profile should be considered if the time response of the simulation is comparatively large and significant. This subsequently leads to research on the convolution effect of point spread functions/Green functions and the source functions in this thesis.

Other researchers considered the polarization and coherency effects of coherent light propagation in turbid media. Tycho et al. [99] calculate the coherency of photons by comparing their total optical path length. Wang et al. [100] have shown the polarization effect of photon propagation in their linearly birefringent system. In terms of photon wavelength, Doyle et al. [101] successfully simulated ocean colour from an ambient environment.

2.3.4 Input - system geometries

One of the powerful MCM features is its capability to simulate light propagation in complex geometries accurately. It can simulate the index-mismatch problem, where the refractive index of the medium is different from the refractive index at the boundaries. Firbank et al. [102] have used it to simulate light propagation of a multi-layered phantom in a confined container. Most researchers used semi-infinite models with either index match or mismatch conditions in their simulations.

For index-match cases, the photons that trespass the boundaries will be absorbed or transmitted. For index-mismatch cases, the photons will either be redirected or transmitted based on Fresnel criteria. The new direction will be determined by using Snell's law.

2.3.5 Input - seawater phase functions and IOP

In terms of Inherent Optical Properties (IOP), the mean cosine of scattering angle, the phase function, the scattering coefficient, and single scattering albedo are the most important parameters in MCM simulation.

V. I. Haltrin [103] has reported several common seawater phase functions used in MCM. These phase functions are derived theoretically and empirically. Analytically, one of the most popular phase functions was proposed by Henyey-Greenstein [104]. Empirically, most seawater Monte Carlo simulations used Petzold phase functions for different water IOP. In order to achieve a fast computation rate, V. I. Haltrin processed them into regressive formulation with 15 sets of coefficients. Recently, he also proposed a one-parameter two-term Henyey Greenstein (TTHG) [105] phase

function for light scattering in seawater conditions, which he claimed to be better than three-parameter TTHG for seawater conditions.

However, it should be noted that these phase functions are derived based on natural waters whereas polluted water normally contains unidentified chemicals or particles. Thus, the phase functions used for Monte Carlo simulation are always an approximation of ocean optics in polluted turbid water conditions, such as harbour waters.

2.3.6 The information processor

The information processor refers to the photon measurement routines. The receiver features include the receiver position, area, Field Of View (FOV), sensor effects, distance, or separation from the source, receiver-to-source angle and the time stamps of receiver response. These factors should mimic the exact measurements, but also need to compromise with the quantization and statistical errors. Larger receiver settings tend to induce higher quantization error, while smaller receiver settings will introduce statistical error due to lower sampling rates.

The simulated receiver measurement is normally taken as a photon accumulator. The quantities could be interpreted as reflectance, transmittance, fluent rate, photon counts, percentile of photon numbers (N), etc. One of the significant MCM features is to categorize the photons based on their scattering orders. This is normally impossible in real world situations. By tracking each photon history, the photons reaching the receiver could be categorized into various groups based on its number of scattering orders. This has enabled detailed insight of multiple scattering phenomena, such as work done by Yang et al. [93], Belov et al. [106], and Bissonnette et al. [107].

2.3.7 Convolution – TPSF and pulse length

The results of spatiotemporal simulation from a MCM run normally correspond to the point spread function of infinite width (impulse input) light pulse function, both spatially and temporally. Thus, if the input function is significant, the system response will have to be convolved with the input source functions. This effect has been well discussed in the literature [89], [106].

Spatially, S. A. Prahl [89] assumed the simulated response as Green's function $G(x,y,z)$ of the medium. An arbitrary irradiation profile could be obtained by convolving the Green's function with the irradiation source function. In a simple

Cartesian coordinate system, he defined the output fluent rate from a complete simulation, $\phi(x, y, z)$ as:

$$\phi(x, y, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(x', y', z') P_0(x - x', y - y') dx' dy' \quad (2.14)$$

The source function $P_0(x, y)$ is assumed to be z independent.

Temporally, the system output in any given time slice $P(t)$ is the convolution between the Temporal Point Spread Function $S(t)$ (TPSF) and the source function. For the case of pulsed LIDAR applications, it should convolve within the half-distance of the ongoing laser pulse. Without considering the geometrical effect and forward scattering issues, Falk et al. [108] defined the backscattering noise, as:

$$P(t) = \int_{v(t-t_0)/2}^{vt/2} S(r) P_0(t - 2r/v) dr \quad (2.15)$$

The laser emits a pulse of power profile $P_0(t)$ starting at $t = 0$ and ending at t_0 and $v =$ light speed in the medium. Numerically, it is convenient for researchers to perform the convolution immediately after the MCM run, such as work done by S. L. Jacques [109].

2.3.8 MCM validation

Another important issue related to the use of MCM is to validate a newly coded MCM. Generally, a MCM code could be validated or compared against three criteria namely: experimental measurement, third party recognized data, and analytical approximations.

Generally, it is recommended to verify the simulation results from experimental measurement. However, the experimental measurement might induce inevitable errors from the sensor readings or system response, such as sensor noises, sensitivity, tolerances of equipment setup, etc. Besides, it is also not possible to verify those simulation results related to photon scattering order analysis. Thus, by comparing some experimental measurements with the simulation's results, the algorithm is generally believed to be valid and fit for other measurements too. Zaccanti [110] verified the MCM codes with detector measurements to predict each recorded photon paths within a diffuse medium. It was subsequently used by Contini et al. [111] to study their imaging system response in the later years. Bissonette et al. [112]

compared their simulation results of LIDAR of multiple FOV with both of the field and the in-situ measurements. They show that the validation of MCM is possible if the true values of the experiments are known.

Third parties results are normally presented in tabulated formats. It is suitable to verify the general quantities of simulation output. However, it is sometimes difficult to further validate the MCM code for system accuracy and parametric sensitivity. In order to compare to third party recognized results, Roze et al. [113] compared their result with data published by Brewster and Yamada [114]. Wang et al. [115] compared their results with van de Haust [116] and Prah et al. [117] simulated outputs. They showed less than 20% relative errors between their results and results published by Prah et al.

Analytical equations are the most robust validation methods for MCM codes. However, the analytical methods are only available for simple and ideal geometrical conditions. Thus, most MCM codes are modelled for simple conditions for verification purposes before they are launched for actual physical conditions. The most frequently used analytical approach in MCM validation is based on diffusion approximation. Chatigny et al. [118] used Diffusion Equations (DE) for their hybrid MCM verification. Their model is set close to the ideal condition in predicting the point spread function in tissues.

From these three approaches, analytical verification of MCM codes is preferred for most of the underwater applications. This is because the underwater imaging conditions have less complex geometry than other applications (e.g. the tissue optics analysis). Normally, the model of boundary-match semi-infinite medium with target reflections is used.

2.4 LIDAR Equations

As explained in Section 1.2, the range-gated imaging system is similar to the pulsed LIDAR technology, except for their design objectives. Thus, the analytical approach to characterize the backscattering effect in LIDAR applications is also applicable to range-gated imaging, except for backscattering from the medium is considered as noise rather than as targeted signal of certain LIDAR applications. In order to analytically investigate the backscattering noise within the reflected target irradiance, it is necessary to review various forms of LIDAR equations that are formulated

empirically or theoretically. The appropriate LIDAR equation provides a means of relating the radiation returned from a probing laser beam/pulse to the relevant optical properties of the target medium. Therefore, it is implicitly assumed that these optical properties can be related to some physical properties of the medium.

Nowadays, the use of Monte Carlo methods has resulted in accurate LIDAR equations derived from well-recognized simulation results.

In its simplest form, the LIDAR equation [119] for plane-polarized radiation and single scattering could be defined as

$$P(r) = \frac{C_1 \beta(\pi, r) e^{-2 \int_0^r C(s) ds}}{r^2} \quad (2.16)$$

$P(r)$ is the probability of a unit of energy received by the receiver, where C_l is the LIDAR constant. It is a function of transmitted power, pulse duration and receiver characteristics. $\beta(\pi, r)$ is assumed to be the volume backscattering coefficient at range r and $C(s)$ is the function of attenuation at distance s .

For the case of a range-gated imaging system, the target irradiance from an opaque target in turbid seawater is normally superimposed with backscattering noise from the medium. This effect is not well documented in the literature. This section attempts to identify the closest form of LIDAR equations that could possibly characterize this phenomenon. The investigated equations should be modelled as functions of transmitted pulse length, pulse profile, detection timing, and duration.

In 1992, Falk et al. [108] proposed Equation 2.15 to study the spatial resolution of Differential Absorption LIDAR (DIAL). The equation is re-quoted as

$$P(t) = \int_{v(t-t_0)/2}^{vt/2} S(r) P_0(t-2r/v) dr \quad \text{where} \quad S(r) = f(r) \beta(\pi, r) e^{-2 \int_0^r \sigma(r') dr'} \quad (2.17)$$

where $f(r)$ is a function taking into account the receiving efficiency of the system and the spatial $1/r^2$ decay of the radiation. $\sigma(r')$ indicates the atmospheric extinction coefficient.

They noticed that most of the LIDAR problems assumed the convolution in Equation 2.15 or 2.17 is negligible. This assumption is true if the time resolution of the receiver is less than (coarser than) the duration of the laser pulse. However, it is not valid for

most range-gated imaging systems where the gate width is generally equal to or shorter than the pulse length. Thus, this analytical approach has offered the mathematical groundwork for backscattering investigation within the target irradiance arriving back to the camera position from an underwater opaque target. It will be further analyzed in Chapter 5.

In 1995, Bissonnette et al. [120] continued to model the single scattering with no scattering radiation other than the backscatter at range r , entering the receiver as

$$P_{ss}(r) = P_0 \frac{vt_0}{2} \frac{A}{r^2} \beta(\pi, r) e^{-2 \int \sigma(r') dr'} \quad (2.18)$$

$P_{ss}(r)$ represents the power received from a single backscattering event of a laser pulse. A is the receiver area. P_0 and t_0 are approximated as the average pulse power and pulse length exerted to the medium respectively. This equation suggests a linear relationship between the outgoing energy P_0 and pulse length t_0 . For the single scattering case, the backscattered energy will remain constant if the multiplier of P_0 and t_0 are the same. This implies a shorter pulse length with higher average pulse power will produce the same $P_{ss}(r)$ as a longer pulse length with lower average pulse power proportionally. This formulation simplifies the actual relationship proposed in Equation 2.17; the convolution effect is approximated as t_0 that is linearly related to $P_{ss}(r)$. This observation is different from Equation 2.17, in terms of the relationship between the average pulse energy and pulse length.

By using the diffusion approximation, Zege et al. [79] established an asymptotic equation for a pulsed source exerted into a turbid medium. They observed that at large time intervals, the detected backscattering noise does not depend on the pulse shape and is determined only by the total pulse energy. This conclusion is similar to Bissonnette's theory described above. For the non-stationary (pulsed source) case, they investigated the irradiance distribution across the beam at the receiver depth. The variance of photon deviation from the axis is much less than in the stationary (continuous wave) case. This means that in a viewing system that accumulates a signal from the object over a short time after its arrival to the detector, the medium Modulation (Modular) Transfer Function (MTF) is essentially better than in the similar stationary source system. However, their results did not analytically describe the improvement of MTF as a function of pulse length and gate timing.

In 1999, Harsdorf et al. [121] has formed an advanced LIDAR equation for fluorescence LIDAR applications. They considered the laser pulse function $P_0(t)$ for single scattering in polluted seawater conditions. In general, they describe the total measured LIDAR signal, $P_t(t)$ in the time domain t could be defined as

$$P_t(t) = P_0(t) \otimes R_m(t) \otimes [\eta \cdot S \cdot \beta(\pi, r) \frac{vt_0}{2} e^{-2 \int_0^r C(r') dr'}] \quad (2.19)$$

where $\otimes$ denotes the convolution in time domain. $R_m(t)$ is the normalized pulse response function of a receiver. η and S represent the system efficiency and sensitivity function of the receiver respectively. This equation has considerably changed the model of a single scattering LIDAR return in the time domain. It implies the dependency on the pulse length and output power is no longer linear. Instead, they are convoluted with the temporal spread function of the medium (bracketed terms in Equation 2.19) and the system response $R_m(t)$.

Similarly, Walker et al. [122] and McLean et al. [123] have rigorously derived the LIDAR equations that include both the detailed physics and some simple approximations for system transfer functions, which become mathematically simple engineering models for system studies. For airborne bathymetry applications (where D is the water depth, H is the airborne altitude of receiver and transmitter), they analyzed the LIDAR for both returns of seabed reflectance and the backscattering of water medium. The sea bottom returns is the targeted irradiance defined as

$$\begin{aligned} \langle P_{bottom}(\zeta) \rangle &= [P_{bottom}(\zeta) \otimes P_0(t)] \\ &\approx Q \frac{AT_{atm}^2 T_{aw}^2 (R/\pi)}{m^2 (H + D/m)^2} e^{-2DK_d} T_{rcvr}(\tau_1) \end{aligned} \quad (2.20)$$

$\langle P_{bottom}(\zeta) \rangle$ represents the convoluted bottom return. $P_{bottom}(\zeta)$, is the temporal point spread function of the sea bottom convoluted with transmitter pulse function $P_0(t)$ in time domain. Q is the energy of an impulse output from the transmitter. $\zeta = D + c\tau_l/(2m)$. τ_l is the multi-path time. m is the water refractive index. R/π approximates the Lambertian seabed reflectivity. K_d is the down-welling irradiance attenuation coefficient. $T_{rcvr}(\tau_l)$ represents a simple multiplier function related to $P_0(t)$. T_{atm} and T_{aw} are the transmission coefficient of the atmospheric and water medium respectively.

The targeted irradiance (sea bottom) is simplified as an exponentially dissipated function with a T_{rcvr} multiplier (P_0 related). This approach is adopted in this thesis to model the target signal $P_S(t)$.

Additionally, they also modelled the backscattering noise of the water medium. By incorporating the multi-path time into a Gamma probability density function, they manage to approximate the water backscattering return as

$$P_{water}(\zeta) \approx Q \frac{A\Omega_{rcvr} T_{atm}^2 T_{aw}^2 \beta(\pi, r)}{\pi m^2 (H + \zeta / m)^2} e^{-2a\zeta} \frac{v}{2} \int_0^{2\zeta/v} A_x(z, \tau_1) d\tau_1 \quad (2.21)$$

In this case, ζ is a virtual distance in the water medium to represent the multiple backscattered energy from the respective depth. $A_x(z, \tau_1)$ is a complex function of Gamma-spread multi-path scattered energy that has self-convoluted over time. Ω_{rcvr} is the receiver field of view.

This model does not include the transmitted pulse function that is significant in the case of short distance range-gated imaging applications. Nevertheless, this thesis observed the upper-limit convolution effect due to the opaque target. The value of $P_{water}(\zeta)$ should dissipate tremendously with the upper-limits $\zeta = D$ (the target distance) while this model assumes the medium is homogeneous without considering $\zeta = D$ as the boundary condition. At $\zeta = D$, the photon is either absorbed or reflected by the opaque sea bottom as P_{bottom} . Thus, the actual backscattered energy will be affected compared to un-bounded case. This situation is especially true in short distance range-gated imaging system applications. This phenomenon will be further discussed in Chapter 5.

2.5 Range-gated Imaging Models

The law governing image transfer through scattering media [79] is obtained by synthesizing the linear system and radiative transfer theories. From the point of optical vision theory, a light scattering medium, such as seawater, is a high frequency filter [59]. The transmission of high frequency signals is reduced considerably in comparison with low frequency signals as a result of light scattering.

In order to analyze the image transfer problems in the spatial frequency domain, it is normally assumed that the scattering level is sufficiently low that only forward

scattering is significant while multiple scattering processes are negligible [124]. Nevertheless, the medium/system modelled must be assumed linear and shift invariant [79]. This assumption may not be true for all conditions. Thus, J. S. Jaffe [125] studied the limits of this assumption in increased turbidity as a function of Attenuation Length (AL).

For the spatial impulse input function, the forward scattering phenomenon is characterized as the Point Spread Function (*PSF*) or medium response of the medium, such as Green's function in Equation 2.14 (in Cartesian coordinates). In this formulation, the effects of imperfections (such as scattering noises) of an imaging system on the image quality are accounted for by a *PSF*. This function is an impulse response of the optical system. By convolving the perfect image of an object with the *PSF*, one obtains the actual image, degraded by imperfections of the system.

It should be noted that the *PSF* is different from Beam Spread Function (*BSF*), though they are sometimes considered equivalent for seawater conditions (small angle scattering approximations) [126], [127]. The *PSF* is the normalized, angular radiance distribution measured at a specified distance from a Lambertian point source. Whereas the *BSF* is the normalized irradiance at the same distance from a collimated source that (the irradiance measurement) is rotated through 4π sr. The angular distribution of $PSF(\theta, r)$ can be measured using a radiance meter or a pin hole imaging system, to focus the radiance on two-dimensional imaging arrays. Thus, the *PSF* is described in the spatial domain (image plane) of an ideal imaging system [128].

By applying a two-dimensional Fourier transform to Equation 2.14 over the coordinates x and y , the Green function (or *PSF*), $G(x,y)$ and initial image irradiance $P_0(x,y)$ can be simply related in the spatial frequency domain (ω_x, ω_y) as,

$$E(\omega_x, \omega_y) = G(\omega_x, \omega_y) P_0(\omega_x, \omega_y) \quad (2.22)$$

In order to avoid introducing too many new symbols, the functions of image output $E(\omega_x, \omega_y)$, $G(\omega_x, \omega_y)$, and the initial image $P_0(\omega_x, \omega_y)$ will be distinguished from their origin by their argument respectively. $G(\omega_x, \omega_y)$ is defined as Optical Transfer Function (*OTF*) of the medium response. The *OTF* is preferable to the *PSF* because of simple multiplication of the spectra in the Fourier domain rather than the intricate

integration in Equation 2.14. Unless the *PSF* satisfies certain symmetry conditions, its Fourier transformed *OTF* is a complex function, having both a magnitude and a phase portion, referred to as the Modulation Transfer Function (*MTF*) and Phase Transfer Function (*PTF*) respectively [124]:

$$OTF(\omega_x, \omega_y) = MTF(\omega_x, \omega_y) e^{-jPTF(\omega_x, \omega_y)} \quad (2.23)$$

The *MTF* is the magnitude response of the medium in the spatial frequency domain. It is sometimes normalized to the modulus of the original/ideal image for various spectra analysis [129], [130], [131].

For underwater imaging conditions, B. L. McGlamery's [132] modelled the image formation into three basic functions. He used the source irradiance distribution function and the water optical properties to produce the following basic image plane irradiance components:

- i) $E_d(x, y)$ - irradiance due to non-scattered light from the object,
- ii) $E_g(x, y)$ - irradiance due to forward scattered light from the object,
- iii) $E_{bt}(x, y)$ - irradiance due to backscattered light from the water.

The working conditions for the model correspond to a monochromatic laser source propagation forming an image in underwater condition. The laser pulses travel from source to target and from the target back to the cameras. The reflection from the target contributes two irradiance components in the image plane: the direct image and the glow field image. The direct image, $E_d(x, y)$, is a high resolution image formed by reflected object light which propagates to the camera without being scattered. The glow field image, $E_g(x, y)$, is a degraded image formed by the reflected object light, which propagates to the camera via forward scattering processes. This approach is well accepted by underwater imaging groups [133], [134]. Each component is easily derived by inverse transform of their respective *MTF* products back to spatial domain.

In range-gated imaging applications, it is generally believed that the backscattering effect $E_{bt}(x, y)$, is negligible due to the fact that the backscattered energy has been range-gated out from the return image irradiance [14]. Thus, the pulse length effect on the image quality is merely a function of target signal strength. This assumption has

hindered the opportunity to optimize the range-gated imaging system in terms of gate timing and transmitted pulse function. Chapter 5 will discuss this issue in depth.

Besides the Monte Carlo simulation, most range-gated imaging models use the traditional apparatus of transfer function to predict the image output of underwater imaging systems. Its modulus, modulation transfer function (*MTF*), an observed quantity has been related to an inherent property, the volume scattering function (*VSF*) with the aid of various approximations [79], such as diffusion approximation, small angle approximation etc. Empirically, the *MTF* could also be determined in a controlled environment, such as work done by Witherspoon et al. [135]. These techniques [125] have been well established in the physics community for various applications, including underwater imaging.

In order to better understand the range-gated image prediction as a function of pulse length, time gating, and opaque target effects, general reviews of the state-of-the-art of range-gated imaging models are needed. The following sections highlight some of the most related range-gated imaging models, and their considerations to predict the image quality or signal to noise ratio with the parameters described above.

2.5.1 Computer modelling by J. S. Jaffe

Jaffe et al. [136], [137] invoked the McGlammery's [132] approach to model the underwater image formation with active, range-gated and scanning imaging system. The calculation of the backscattered component is not linear as the backscattered light enters the camera from a large distribution of angles. Thus, the small angle approximation used in computing the forward scattered component is no longer valid. They considered that the three-dimensional space between camera and the target plane is sliced into planes of thickness Δr that are parallel to the image plane of the camera. The irradiance incident upon each of these planes, $E_s(x, y, z)$ is then calculated by computing the direct component, adding an additional amount of irradiance due to the light that is forward scattered.

By taking a weighted superposition of the intensities from a given slice Δr , the backscattered energy reflected towards the camera element x, y due to the volume ΔV of Δr can be defined as

$$E_{bt,d}(x, y) = \sum_{i=1}^N e^{-CR_i} \frac{\beta(\pi, r)}{4f_n^2} E_s(x, y, R) \pi \Delta r T_{lens} \cos^3 \theta \left[\frac{R_i - F}{R_i} \right]^2 \quad (2.24)$$

R_i is the distance from a point in the camera to the centre of the backscatter slab. f_n is the f-number of the camera lens, C is the total attenuation coefficient, F is the focal length and θ is the angle between the reflected plane with camera line of sight. The value N denotes the first backscatter plane ($i=1$) to the plane adjacent to the target ($i=N$). The total scalar irradiance due to the backscattered image $E_{bt}(x, y)$ can then be calculated by adding an additional forward scattered component as

$$E_{bt}(x, y) = E_{bt,d}(x, y) + E_{bt,d}(x, y) \otimes G(x, y) \quad (2.25)$$

For a range-gated imaging system, the backscattering noise is modelled as the component backscattered energy at $i=N$ only without the summation of all backscattered plane. They generally perceived that the longer pulse length enables more power collected per pulse by the camera, but the amount of backscattered noise will subsequently be increased too.

This phenomenon will be mathematically derived as the convolution with fixed upper-limits in Chapter 5. By describing the phenomenon mathematically, the optimization of range-gated operation to achieve highest image quality is possible.

2.5.2 Imaging models for underwater range-gated imaging systems

It is worth noting that, M. P. Strand [39][138] has modelled time dependent point spread function and modulation transfer functions to estimate the range-gated image for various gate widths. Monte Carlo techniques are used to compute aspects of optical propagation in water based on the IOP defined. He has shown that the time dependent *MTF* can be obtained from the point spread function, a function of Fourier spatial variables with Volume Scattering Function (*VSF*) parameters.

Unfortunately, his model neglects the backscattering effects within the target image irradiance. Without a mathematical model to describe the phenomenon analytically, it is sometimes difficult to explain physically how an image quality could be better with shorter pulse length and gate time if the amount of energy per pulse is still the same.

In the following years, McLean et al. [39] showed that front RITP (our newly defined terms, see Chapter 3 for the definitions) gated images are better by using Monte Carlo

simulation without considering the backscattering noise within the target irradiance (actual RITP) itself. This conclusion has been well agreed in trans-illuminated time-gated imaging models, such as in work done by Marengo et al. [139], Gopal et al. [140]. They considered the photons trans-illuminated over a turbid medium in three categories only, namely: ballistic, diffuse, quasi-ballistic components. The ballistic component is the photons that have not undergone any scattering. The diffuse component is the photons that are completely randomized directionally. The quasi-ballistic component is the photons that have undergone more than one scattering event but is still travelling in approximately the same direction as it did when it entered the medium. They treated diffusely scattered target signals as unwanted noise in their applications.

If the backscattering noise within the target irradiance is not significant compared to the target signal, the trans-illumination models are suitable in predicting the reflected range-gated imaging system, where the camera and the laser source are opposite the target behind the turbid medium. However, this situation is not always true for nanosecond pulse lengths (or/and gate widths) in near target (a few meters) range-gated imaging applications. Backscattering noise is still visible in this turbid condition with the illumination source and the camera in proximity. The analysis is further complicated if multiply scattered photons are dominant in increased target distances, as some of the multiply scattered signals are desired signal as long as the target information is reserved. This will be discussed in detail in Chapter 3.

2.5.3 Generic LIDAR model by McBride et al.

The model proposed by McBride et al. [141] used Modulation Transfer Functions (*MTF*) to incorporate environmental influences on image detection and blurring. These parameters include absorption, the depth-dependent effect of a scattering layer within the atmosphere and water columns, backscattering, bottom and target reflectivity, wind driven air/sea interface changes. System parameters include source/receiver geometry, various spot and scan configurations, optical defocusing, and power. System electronic and image processing are also being incorporated. The model is used for range-gated imaging systems and Continuous Wave (CW) laser line scanner imaging systems.

For range-gated imaging systems, it calculates the backscattering effect separately from the core model. The backscatter algorithm, taken from W. H. Wells [142], assumes cylindrical symmetry about both the source and receiver bore sights and evaluates the resulting one-dimensional integral in real time. Its output gives the backscatter contribution as a function of depth with thickness equal to the distance travelled by the front of the pulse over half its duration. It needs manual adjustment to include the backscattering in the time domain without considering the variation of backscattering noise or incorporating the opaque target effect.

2.5.4 Computer based underwater imaging analysis by Fournier et al.

The model proposed by Fournier et al. [143] is applicable to standard light source (parallel system), range-gated imaging, and laser line scanning illumination. The framework for this computer model is based on an approximation of the phase function, analytic expression for the mean square angle, the beam spread function (*BSF*), as well as the modulation transfer function (*MTF*).

The imaging model is based on McGlamery's [132] approach, which follows a formalism of conventional imaging systems. The dominating *PSF* term due to light scattering by seawater depends on the distance (in water) between a point in the object and a conjugate point in the image.

For a given range-gated imaging system, the time dependency of the image is modelled by using several discrete image time layers. Each layer is the image received within time interval t_i, t_{i+1} , for $i = 1$ to N , where $t_{i+1} - t_i$ is the time gate width. Any non-linear effects related to the increase in the instantaneous power of the pulsed illumination and other effects of the short time scale are neglected.

The image is calculated by using the concept of reverse projection: each image pixel is projected onto the scene, cutting a diverging rod of water. All light reaching the pixel must originate from within that rod. This simplifies the calculations of contribution to the image from the scene.

The scattering function, the attenuation coefficient, and the Beam Spread Function (*BSF*) of seawater affect the quality of the image. In the imaging model, the *BSF* is calculated by using a small angle scattering approximation [144]. Given the illumination pattern, one can multiply the image from the range-gated camera by its inverse to produce a uniformly illuminated picture.

They formulated a complete normalized *MTF* of a medium that scatters and absorbs light. It is basically a function of IOP of seawater, target distance, and spatial frequency of the target image. The variation of backscattering noise within the target plane slab and the gate timing issues are neglected.

2.6 Chapter Summary

This chapter gives an overview of light propagation theories with the consideration of pulse length, gate timing, and opaque target effects. Though range-gated imaging systems have been used and studied for more than 30 years, the optimization of these systems in terms of gate timings and pulse lengths and evaluation procedures are not well documented. The reason is unknown to us.

This is partly due to the lack of an analytical solution to clarify the backscattering effect (as a function of pulse length, pulse function, and gate timing) superimposed with the target irradiance. As an example, Witherspoon et al. [37] and McLean et al. [39] have contradicted conclusions based on their experimental and numerical solutions respectively. This thesis attempts to analyze their observations in terms of backscattering noise variation within the Reflected Image Temporal Profile (RITP, defined in Chapter 3).

From this analysis, the tail-RITP gating concept is experimented and simulated. The results show this technique can optimize the range-gated image quality for short target distance and turbid water conditions. This has qualitatively determined one of the optimization techniques in future range-gated imaging system design.

In order to fine-tune the image quality in an optimization process, two quantitative approaches are suggested to serve as the performance index feedback to the imaging control system. There are the underwater visibility index and the quantitative image quality index. The latter is preferred for near target range-gated imaging system application in this thesis.

In conclusion, most LIDAR and imaging models assume no variation of backscattering noise due to opaque target effects. Some of them have even neglected the backscattering noise of gated images in turbid water conditions. This has subsequently led to various assumptions to discard or simplify the backscattering issues in their models (as explained in Section 2.4 & 2.5).

On the other hand, most researchers believe shorter pulse length and/or gate time will result in better range-gated image quality. It is normally understood that if a transmitted pulse becomes shorter, keeping the same pulse energy, the backscattering noise practically does not change, but the peak value of the power of the target signal increases. It leads to the increase of the signal-to-background ratio. However, this understanding may not be able to explain correctly how shorter pulse lengths have lead to better Signal to Backscattering Noise Ratio (SBR) if the receiving camera is considered as a light energy integration device. For example, the total target signal energy is 1 Joule per pulse with a longer gate time of 6 ns and pulse length of 6 ns. If a shorter pulse is used, e. g. 3 ns, with the same amount of energy, the total amount of target signal integrated by the camera is still 1 Joule per pulse, even though the peak energy has increased 2 times (assuming the same pulse shape). From SBR calculation, if the camera gate time is 3 ns or 6 ns, the integrated target signal $P_S(t)$ is still the same. Thus, in order to explain the improved SBR, the backscattering noise has to be reduced due to shorter pulse length. It is a correction of backscattering noise with the RITP in terms of the physical understanding.

This analysis has led to the analytical works on relating the Signal to Backscattering Noise Ratio (SBR) and the image quality. In order to further verify this theory, the Monte Carlo methods are reviewed. They will be used to simulate the light pulse propagation of diverged beam in turbid medium.

CHAPTER 3

THE MONTE CARLO METHOD FOR REFLECTED IMAGE TEMPORAL PROFILE (MCRITP)

This chapter focuses on the introduction of a newly defined term, Reflected Image Temporal Profile (RITP). This includes the definitions and decomposition of RITP into multiple sub-components. In order to examine the diverged beam propagation in complex geometry, the Monte Carlo method is used to simulate the stochastic nature of photon particles propagating in homogeneous turbid medium (Henyey Greentain phase function is adopted). This simulation model is verified with Yaroslavsky's model and experimental results.

3.1 Introduction

For underwater range-gated imaging systems, the receiver is adjacent to the light source while the target is behind the scattering medium. Thus, the Reflected Image Temporal Profile (RITP) is observed in the time domain as a super-position of a single target reflection and the backscattering noise. For an infinite length light pulse (impulse input) exerted into the medium, the backscattered energy at the receiver is modelled using a Temporal Point Spread Function [145] (TPSF), which represents the reflectance from the medium. The RITP is formed when the TPSF and target irradiance convolve with an approximately Gaussian [146] pulse produced by the illuminator (light source) spatially. The Gaussian pulse can be predefined or measured in the experiment. Therefore, the RITP is perceived as the convolution of an outgoing pulse with the Reflected TPSF-Target kernel function (see Chapter 5). The TPSF-Target kernel function could be simulated with numerical methods, such as Monte Carlo simulation.

An example shown in Figure 3.1 is the RITP captured in laboratory conditions by using a silicon detector from Newport [147] with about 1.8 meters target distance [148]. Qualitatively, the RITP could be sub-divided into various time intervals, with each time slice containing different compositions of photons coming from backscattering noise, target signal, signal scattered noise etc.

The first peaked response measured at the detector/source is considered as Backscattering Peak (BP). It normally occurs at the mean scattering time of pulse

propagation in an extended homogeneous medium [149]. If the pulse length effect is significant, the peak is normally off centred (mean scattering time plus half pulse length) within the total pulse length. The actual Reflected Image Temporal Profile (actual RITP, see Figure 3.1) indicates the target irradiance interval that has superimposed with the backscattering noise. It is the desired temporal interval for range-gated imaging system. In order to investigate the Signal to Backscattering Noise Ratio (SBR) within the RITP, the actual RITP could be sub-divided into three basic regions. With single-target-single-pulse configuration, these regions are Front RITP, Middle RITP, and Tail RITP regions (see Figure 3.1). Each region is believed to contain different SBR based on results reported by Witherspoon et al. [37], and Gilbert et al.[150].

Assuming the light is modelled as individual photons interacting with each other independently, the received energy can be modelled as an additive combination of individual photons based on their history. Their combinations in any time instance will result in different image quality [37], [150]. Bissonette et al. [112], [151] categorized the photons into different groups based on their historical happening, such as direct photons, single forward scattered photons, multiply scattered and

backscattered photons. Those photon groups have been linearly summed up to obtain the total reflected energy. Alternatively, Zege et al. [152] separated the returning energy from various layers of scattering media, such as water, atmosphere, water surface and underwater target. In this thesis, Bissonette's approach is used to categorize the photons based on their individual history. The RITP energy received at any time instance from the scattering medium can be described as

$$P(t) = P_{BSN}(t) + P_S(t) + P_{SMM}(t) \quad (3.1)$$

where $P_{BSN}(t)$ contains the single and multiple backscattering noise from turbid medium and excluding target reflected photons within the receiver field of view (FOV).

$P_S(t)$ contains the direct or forward scattered target reflected photons within the FOV which is the desired signal in range-gated imaging system.

$P_{SMM}(t)$ contains the target reflected photons within the FOV which have been multiply scattered so that target information is lost.

The backscattering noise $P_{BSN}(t)$ is initiated at the entrance of the medium and dissipates to produce a “tail” due to its attenuated energy and optical ringing effects[150]. The target signal $P_S(t)$ and signal scattered noise $P_{SMM}(t)$ contains photons from the target. On the way back to the receiver, they superimpose with the backscattering noise $P_{BSN}(t)$.

In order to quantify the SBR, the photons returning to the receiver should be further classified into 18 groups based on their history. As shown in Figure 3.2, Equation 3.1 is further divided based on this classification:

$$P_{BSN}(t) = P_{DBD}(t) + P_{GBD}(t) + P_{DBG}(t) + P_{GBG}(t) + P_{DBM}(t) + P_{GBM}(t) + P_{MBD}(t) + P_{MBG}(t) + P_{MBM}(t) \quad (3.2)$$

$$P_S(t) = P_{DTD}(t) + P_{DTG}(t) + P_{GTD}(t) + P_{GTG}(t) + P_{MTD}(t) + P_{MTG}(t) \quad (3.3)$$

$$P_{SMM}(t) = P_{DTM}(t) + P_{GTM}(t) + P_{MTM}(t) \quad (3.4)$$

Each photon group in Equations 3.2-3.4 is indexed using the following notation:

D – direct travelling with no scattering,

B – backscattering from the medium,

G – forward small angle scattering,

T – target reflection, and

M – multiple scattering.

For example, $P_{DTD}(t)$ is defined as photons which travel directly to the target (D), reflect from the target (T), and arrive back at the receiver aperture without any interaction with the turbid medium (D). $P_{DTD}(t)$ always takes the shortest time to convey the target signal back to the receiver.

$P_{MTG}(t)$ represents the photons which reach the target surface after multiple scattering (M), reflection (T) and return to the receiver with some forward scattering (G). Thus, $P_{MTG}(t)$ will be the later part of RITP signal compared to $P_{DTD}(t)$.

Generally, $P_{BSN}(t)$ and $P_{SMM}(t)$ increase proportionally, while $P_S(t)$ is reduced under increased scattering conditions. For near target turbid seawater and narrow FOV, Walker et al. [122] justified the light pulse propagation as a dispersion-less system,

where the multi-path time is small and negligible compared with the pulse length. As the scattered target bearing photon's ($P_{SMM}(t)$) response is a function of multi-path time, it is also negligible in our considerations here. However, it should be noted that $P_{SMM}(t)$ will be higher than $P_{BSN}(t)$ for higher attenuation length and wider FOV conditions when the multi path time is significant. $P_{SMM}(t)$ should be considered in higher attenuation lengths and wider FOV conditions in future works.

3.2 The Monte Carlo Simulation

As described in Chapter 2, the Monte Carlo method has been used because of its simplicity for complex geometry and because it provides better accuracy than an approximated approach [79], [153]. By using this method, it is possible to simulate light propagation in homogeneous semi-infinite turbid medium across target distance r_0 . The TPSF from both scattering media and underwater targets can be estimated. Convolution of the outgoing pulse with the TPSF produces each component in Equation 3.1. The backscattering noise $P_{BSN}(t)$ is defined as the non-target reflected energy returning to the receiver position within the Field Of View (FOV). The target signal $P_S(t)$ is assumed to consist of photons reflected by a Lambertian target with reflectivity R , arriving at the receiver position within the FOV. It is assumed that the signal scattered noise $P_{SMM}(t)$ is negligible compared to $P_{BSN}(t)$ within small FOV and short target distance (less than 10 Attenuation Length, AL [122], [154]).

The Monte Carlo code used has been modified from S. L. Jacques' [155] publicly available code. S. Jacques's codes were written to address and verified the multi-layered light propagation issues with the time domain considerations. This project used the verified codes (as illustrated in Section 2.3.1) and modified it in the time resolved light propagation problems. In this thesis, it is referred as MCRITP (Monte Carlo for Reflected Image Temporal Profile) for time resolved model. MCRITP is currently modelled based on boundary matched semi-infinite geometry. Part of the algorithm is used to simulate photons reflected from a Lambertian target perpendicular to and at a pre-defined distance from the source. Figure 3.3 illustrates the algorithm in flowchart for a complete run.

As shown in Figure 3.3, MCRITP is a variable step size Monte Carlo system, which is determined by a random number *rand* and the following equation:

$$step = -\ln(rand) / C \quad (3.5)$$

The scattering direction is derived from the Henyey-Greenstein phase function [153]. Detail equations are available in Appendix B. For variance reduction, each photon is launched from a point source within a predefined FOI (Field of Illumination), with weighting factor 1.0 (100%) attributed to the photon [77].

The receiver aperture is a circular irradiance receiver with a predefined radius and FOV. Photon reflection from the target is modelled by the target reflectivity and random direction functions. For each MCRITP run, the photons collected at the receiver aperture are kept in three separated channels, namely Channel A, B, and C. Channel A contains target reflected photons received within the receiver FOV. Channel B includes both target signal and backscattering photons within the FOV. Channel C records the photons that fall within the receiver area but outside the FOV (just for verification purpose). Those photons that fell out of the receiver aperture area are omitted. In this thesis, only Channels A and B will be used.

MCRITP is modelled as a mono-static or close to mono-static condition, with small separation between source and receiver (0.1 or 0.2 m apart). This situation is consistent with most of the dexterous underwater vehicle imaging system conditions. Polarization, multiple wavelengths, and coherence effects have not been considered here (not relevant to this thesis). Target reflectivity is temporarily taken as 100%. It is normalized and set equal to one.

It should be noted that the Monte Carlo results always contain inherent quantization and statistical errors [98]. With smaller receiver apertures and shorter time stamps, the simulated results have higher statistical errors while larger receiver apertures and longer time stamps tend to increase the quantization errors. Therefore, cautious measures should be taken to compromise these inherent errors to achieve reliable results. This involves both verification and error check analysis.

3.3 MCRITP Model Verification

The Monte Carlo algorithm has been implemented to predict photon propagation within a scattering medium. The core algorithm, such as shown in Figure 3.3, is basically an iterative computation based on its random number generator and respective probability density functions. The complex aggregation of computation is sometimes considered as a “black box” operation. Therefore, we believe the simulation results need to be validated and verified by comparing the outputs to a reliable source of references, such as analytical, experimental or third party’s results (explained in Section 2.3.8).

MCRITP simulates light propagation for short target distances and source-receiver separations. However, most of the analytical approaches, such as diffusion equations [156], are valid only when photons have gone through enough scattering events. In other words, it implies that the theories are valid only for shorter transport mean free paths or wider source-receiver separations. For such cases, Wilson’s [157] approach can be used to preliminarily validate the MCRITP results (see the following equation).

For the MCRITP parametric set up as shown in Figure 3.4, it is run to simulate the total reflectance collected with an infinite receiver area at the plane coincident with the point source at a very small Field of Illumination (FOI). Figure 3.5 illustrates the comparison between MCRITP results and the total reflectance $R_T(t)$, where

$$R_T(t) \propto t^{-3/2} e^{-avt} \quad (3.6)$$

a is the absorption coefficient, and v is the light speed in the medium.

In Figure 3.5, one million photons per simulated condition (takes about 5 minutes on 1.6 GHz Pentium IV computer), the scattering coefficient B is fixed at 1.5/m while the absorption coefficient is varying to achieve different levels of single scattering albedo, B/C (C is the attenuation coefficient). The MCRITP results agree well with the Diffusion Approximation (DA) results, especially at high albedo (> 0.95). For lower albedo, MCRITP shows high correlation with analytical results at larger attenuation length (e.g. more than 10 attenuation length or longer time range). For albedo = 0.95 and 0.67, 10 attenuation lengths equals to time response at 56 ns and 40 ns respectively.

Figure 3.5 shows disagreement between MCRITP and the analytical results at shorter time intervals. It is due to the theoretical assumption that the light scattering delay (t_l)

is not significant compared to the mean time of flight between interactions (t_2). Therefore, Yaroslavsky's [158] model should be used to verify MCRITP results for short scattering distances where $t_1 > t_2$ or $t_1 \gg t_2$.

Yaroslavsky et al. [158] define t_1 and t_2 time as:

$$t_1 = \frac{\int_0^{\infty} t f(t) dt}{\int_0^{\infty} f(t) dt} \quad ; \quad t_2 = 1 / C v \quad (3.7)$$

where $f(t)$ is the temporal point spread function of the medium.

Yaroslavsky et al. have modified the standard diffusion equation by including the influence of scattering delay to the temporal point spread function of the scattering medium. For matched boundary conditions, they modified Patterson's model [156] by replacing v with the transport velocity v_{eff} . Temporally, the reflectance collected at ρ distance from the source is defined as

$$R(\rho, t) = \left(\frac{4\pi v_{eff}}{3\mu_{tr}} \right)^{-3/2} z_0 t^{-5/2} e^{-av_{eff}t} e^{-3\mu_{tr}(\rho^2 + z_0^2)/(4v_{eff}t)} \quad (3.8)$$

$$v_{eff} = v_o / n_{eff}; \quad n_{eff} = n + t_1 B v_0; \quad \mu_{tr} = B(1 - g) + a \quad (3.9)$$

ρ is the source receiver separation, v_0 is the light speed in vacuum, n is the refractive index, g is the asymmetric parameter of scattering indicatrix, z_0 is the effective source approximation ($z_0 = 1/\mu_{tr}$).

Equations 3.7, 3.8 and 3.9 depict the reflectance of a collimated point source received at a distance ρ with a pinhole receiving area. However, the Monte Carlo simulation would always require an adequate receiving area or discrete coordinate closure to accumulate photons arriving at the receiver. For this verification, the receiving area has been arbitrarily chosen as 0.5 m in diameter as a compromise between an increase of quantization error and an increase of statistical error (large receiving area might cause higher quantization error while smaller receiving area will increase the statistical error). Figure 3.6 illustrates the parametric set up of MCRITP run to verify against Equation 3.8. At each turbidity level, the medium responses for both simulated and analytical results are normalized to their own maximum values respectively.

With mono-static or close to mono-static source-receiver separation, the effective response times of the temporal point spread function (TPSF) are shorter than the imaginative source-receiver separation in the diffusion equation [159],[160]. Hence, the predictions from Equation 3.8 should be compared at the same initial point. This approach is similar to the work done by Bruce et al. [161] to verify a universal function of TPSF for different sample widths in highly scattering medium. They reported that the time offset between the analytical and experimental results should be moved to the same initial point to permit direct comparison. Subsequently, the results from Equation 3.8 were offset with 7 nanoseconds (higher turbidity levels) to 15 nanoseconds (lower turbidity levels) earlier. At these offsets, the analytical results show the same response in terms of light intensity as predicted by MCRITP.

With five million photon simulations performed on the same computer (a 1.6 GHz Pentium PC), it takes about 90 minutes for each complete run in the respectively turbidity level. Figure 3.6 illustrates the comparison between MCRITP results for semi-infinite model with non-absorbing media. For short range backscattering

reflections from the turbid medium, the maximum relative error for each turbidity level is 6%, 10%, 15%, 19% for 1.0/m, 1.5/m, 2.0/m, 3.0/m scattering coefficient respectively.

MCRITP in Figures 3.5 and 3.7 has shown good agreement with Equations 3.6 and 3.8 respectively. For range-gated imaging systems, the pulse length effect might be significant especially when the target range is short enough. In this condition, the actual RITP responses ($P_{BSN}(t)$, $P_S(t)$ and $P_{SMM}(t)$) are affected by the outgoing laser pulse length. Therefore, the TPSF should convolve with outgoing temporal function to calculate the actual signal to noise ratio within the RITP.

In order to verify the MCRITP convolution results, an experiment was carried out to study the accuracy of MCRITP simulation. A 3×1×1 meter water tank was used to simulate an open sea (semi-infinite) model, it was internally lined with heavy black cloth to absorb laser energy at the walls. A photo-detector (0.003 m receiver radius and about 50° FOV) was placed close to the water tank window. The photo-detector was positioned and directed towards the opposite side of the tank, but protected from

the laser source refraction/reflection from the laser diverging lens and water tank's glass sides (behind the camera block and attached to the glass window).

The experiment used a Nd:YAG laser (less than 140 mJ per pulse [162]) with about 6 ns FWHM (Full Wave Half Maximum) pulse at 20 Hz. The laser has been diverged into 20° FOI in turbid water simulated by Mylanta [148]. The attenuation and absorption coefficients were measured by AC9 from Wetlab [163]. Chapter 4 illustrates the experiment setup and Figure 4.12 shows the intensity profile captured by the photo-detector.

The outgoing power profile is defined as

$$P_0(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(t-100)^2/\sigma^2} \quad (3.10)$$

with central axis at $100 \times 0.1 \text{ ns} = 10 \text{ ns}$, $\sigma = 30 \times 0.1 \text{ ns} = 3 \text{ ns}$. 0.1 ns denotes the time step of each data point (for 100 simulated data points). Figure 3.8 illustrates the parametric set up of MCRITP to simulate the TPSF before the convolution with Equation 3.10.

Due to the significant noise level for the photo-detector at low turbidity level (lower reflectance intensity), only the experimental results in higher turbidity level were taken to compare with MCRITP results. Both data sets were normalized by the respective peak values at $C = 5.9/\text{m}$ for all turbidity levels. Figure 3.9 depicts the comparison between the experimental measurements and convoluted MCRITP results. It shows high correspondence between the convoluted simulation and experimental results.

As shown in Figures 3.5, 3.7 and 3.9, the MCRITP results have been compared with the analytical approach based on Wilson's[157], Yaroslavsky's[158] models and most importantly with the experimental results. Figures 3.7 and 3.9 show that the relative errors between MCRITP and the testing data sets are less than 20% (or +/- 10%) within the range of interest. It was normally accepted for typical Monte Carlo verifications [145].

It is believed that the errors are mostly caused by the inherent quantization and statistical errors of MCRITP. Figure 3.7 shows a systematic shift of relative error in increased scattering coefficients. The relative error is attributed to the aperture size

quantification offset as it is not relevant in the modified diffusion equation. The systematic errors and noise effects of equipment also contribute to the error, as shown by fluctuating experimental data points in Figure 3.9. Since sensor dark noise is about 10% of normalized intensity, the MCRITP is only compared to the experimental data higher than 20% of the normalized peak intensity.

This constant shift of relative error can be neglected if the simulation results were compared only for their relative values. This approach is also applicable in Chapter 5. With high correspondence between the MCRITP results and the testing data set, the MCRITP algorithm has been validated within the range of interest.

3.4 Chapter Conclusion

In this chapter, a newly defined term is introduced as Reflected Image Temporal Profile (RITP). It is defined as the convolution of the outgoing pulse function with the reflected TPSF-Target kernel function. Practically, it describes the timely characteristics of target irradiance and backscattering noise superimposed with each other at the receiver aperture. The RITP is coarsely divided into several time intervals, which contain different levels of Signal to Backscattering Noise Ratio (SBR). In order

to analyze the variation of SBR within the RITP, Monte Carlo for RITP (MCRITP) is coded and verified in time domain.

The MCRITP is first compared with Wilson's model. It is valid for longer scattering length/travelling distance. The Yaroslavsky approach is used to characterize the temporal response at shorter scattering distances from the source. The MCRITP agrees with this model with adjusted offset. This is also the first experimental demonstration of Yaroslavsky's model accounting for scattering delay time larger than the mean time of flight between interaction, such as highly forward scattering phenomenon in seawater conditions. Most importantly, the MCRITP shows good correlation with experimental results after its convolution with the Gaussian outgoing pulse function.

For current MCRITP simulations, the simulated geometry is a semi-infinite model without target laid in front of the laser and camera. The reflections or absorptions from sidewalls are considered negligible compared to the total backscattering noise from the medium. Hence, there is room for improvement for the MCRITP, the reflection from the sidewalls should be included in future work to further enhance the simulation results in this laboratory condition. Besides, various variance reduction schemes should also be used to reduce the statistical error for small receiver areas while not sacrificing the computation time.

This simulation emphasizes light propagation at short target ranges in turbid seawater, which is also the main focus of most recent underwater range-gated imaging system developments, typically by He et al. [19], Grace et al. [31], and Sakai et al. [42].

CHAPTER 4

SYSTEM ANALYSIS AND LABORATORY SETUP

This chapter describes the hardware setup of the range-gated imaging system in a laboratory condition together with the timing diagrams in nanosecond scales. This includes a preliminary analysis of each component in the system to enable better equipment selection and design works in actual prototype developments. By simulating turbid water condition with Mylanta®, the gated and non-gated imaging systems are compared to evaluate the performance of current range-gated imaging systems (tested with United State Air Force (USAF) target images). The output image quality is correlated to the actual performance of the system with quantitative scales. The Modified Fidelity (*MF*) index shows its adequacy for this purpose.

4.1 System Introduction and Timing Diagram

In order to research the optimization techniques, a range-gated imaging system is built in a laboratory configuration as the engineering test-bed for future NTU range-gated imaging system. The basic framework for the actual underwater imaging system is similar to this setup. It generally consists of eight major components, namely: laser system, lenses assembly for laser and camera, ICCD (Intensified Charge Coupled Device) camera and its control unit, delay generator (or control unit in future), waterproofing container, power supplies, interfaces (frame grabber or digital video converter etc), and the relevant optical measurement devices.

The tests are carried out in a transparent water tank with internal cloth lining to absorb most light energy scattered onto it. Apart from this, an attenuation meter is added into the water tank to measure the optical properties of water.

The general layout of the current system is illustrated in Section 4.1.1 together with its signal flow diagram. Each individual component is investigated in the later sections to establish accurate design specifications and considerations for future developments. Detailed operating instructions are found in their respective manuals. Lastly, all related equipment settings for this project are summarized in Appendix C to ensure that the exact procedure and equipment setup can be reproduced in future.

4.1.1 General layout of current range-gated imaging system

From Figure 4.1, the current system components are huge and not immersible in water, the future design could be modified and scaled down for underwater portable applications which includes Field Programmable Gate Arrays (FPGA), diode pumped laser etc.

Figure 4.1 General equipment layout (Picture)

From Figure 4.2, the current range-gated imaging system shows that the video output from the ICCD camera is connected to the computer via a frame grabber as well as a SNAZZI analog/digital video converter and a Camera Control Unit (CCU-01). PCU providing continuous 15Hz TTL (Transistor-Transistor Logic) pulse to the laser head and Delay Generator (DG535). This timing is synchronously relayed to the camera control unit to trigger or open the intensifier gate.

For optical measurement devices, there is an Attenuation Meter (AC9) measuring the optical properties of water at the other end of water tank. A photodetector, which is protected against the laser reflection from the tank's wall, is placed beside the camera to trace the temporal profile of returning signals. Its output is connected to a high sampling rate oscilloscope (Not shown in the diagram).

As shown in Figure 4.3, the range gating process starts from the PCU (Power/Cooling Unit) of the laser system. This unit basically controls the frequencies and power output of the laser head (Surelite Laser [164]). In the PCU, the flash lamp is charging at 15 Hz repetition rate (preset). The signal from this control logic is synchronizing the other components in the system. This signal is set low to trigger the Delay Generator, DG535 [46] whenever the flash lamp starts.

In the DG535, the signal from the PCU is delayed and relayed to the following equipment: The first output of DG535 is dedicated to the camera control unit, CCU-01 [165], to set the gate opening time and gate duration. The camera gate time signal from the DG535 is by passed through the CCU unit to the camera. It is synchronized with the reflected target signal. The second output of the DG535 triggers the frame grabber, MII card [45]. The frame grabber will capture the video/image output from the camera. Besides the frame grabber, the video output from Xybion [166] camera is also continuously recorded as a MPEG2 movie clip with the SNAZZI III [167] interfaced to the personal computer for demonstration and real time purposes.

In the same time, there is a high speed photodetector [147] placed side by side with the camera. The detector has the capability to trace the reflected signal temporally. For monitoring purposes, all important signals are connected to a digital oscilloscope parallel to their functional connections. This includes a flash lamp output from the PCU, gate time delay from the DG535 and the camera gate timing and duration

readouts. It is observed that the actual gate profile always deviates (shortened) from the input gate profile for shorter gate durations (<30 ns). It is due to the system nonlinear response in very short gate duration.

For current setup, the photodetector is connected to an oscilloscope with a 5 giga-samples/second. Up to three thousand acquisition points could be recorded in text file format for further processing. It is proposed to engage the photodetector as a LIDAR detector as well as the turbidity measurement device in future.

4.1.2 Timing Diagram

From Figure 4.4, the system operates from its initial flash lamp synchronizing signal. Each image acquisition cycle is initiated when a TTL low signal (that is triggered for about 20 microseconds) from the PCU turns on the flash lamp. For Q-switch setting

of 150 microseconds, there will be about 150 microseconds of delay before the laser head starts to exert the laser pulse [164] (T_1 delay with pulse length t_p).

This signal from the PCU would propagate through cable lines that induce a few nanoseconds delay, to the input of the delay generator, DG535. In addition, there are some tens of nanoseconds of inherent delay internally induced in the DG535. Thus, the actual delay (T) applied to the DG535 would happen only after those inevitable delays. T_2 is the delay time of the DG535 output after a TTL low on input gate is detected (T_2 delay, with duration t_2 , camera gate input).

The DG535 output goes into the CCU-01 unit with by-pass mode, which means the actual TTL low signal from the DG535 has been directed to the camera gate intensifier circuit. Again, there are also some inevitable 80 ns delays between the DG535 input and the actual camera responses (T_3 delay, with effective gate duration t_3).

Assuming there is only one target hit by the laser pulse that returns to the camera after sometime from the lasing events, the period between the lasing and the reflected image signal is T_4 . If $t_p = t_3$, the delay timing to capture the reflected target signal has to satisfy: (as shown in Figure 4.4)

$$T_1 + T_4 = T_2 + T_3 \quad (4.1)$$

System instability and jittering are omitted here. Subsequently, the delays needed to be adjusted by T that can be approximated as:

$$T = T_1 + T_4 - (T_3 - \text{minimum delay of DG535}) \quad (4.2)$$

By using Equation 4.2, the camera gate timing could be determined based on the total lasing process plus the time of flight of the laser pulse. Additionally, the second output of the DG535 will be set to trigger the frame grabber to capture the video output from the camera as still images. This delaying interval is T_5 from the flash lamp synchronous signal.

4.2 System Components

The following sections describe each component in detail. We highlight the respective equipment specifications and design considerations for future system development. The equipment specifications are important for acquisition and procurement of appropriate commercial products, such as laser, camera etc. While the design considerations are the fundamental elements in designing an optimized system, this is compromised with various physical constraints, such as cost, weight, power consumption, and size.

This work has served as the supporting ground to appropriately select and design equipment for actual deployments of range-gated imaging systems in future. Figure 4.5 illustrates the general design layout for each sub-component of a range-gated imaging system. It consists of eight components that are self-explained in the figure.

From an operation point of view, the Reflected Image Temporal Profile (RITP) is taken as an unknown to the system. The target range and water turbidity are possibly estimated with the optical measurement tools, such as a LIDAR detector and attenuation meter. Thus, the focusing lens and camera gate time could be appropriately adjusted based on the LIDAR and turbidity input. The camera gain

could be adjusted with automatic gain control or by manual intervention. For remote operating conditions, the system should be equipped with online image processing and self-tuning control functions. This will reduce the communication burdens between the surface control and the underwater imaging system. The results can be delivered as digital data for machine vision applications or standard video for human visual observations. In order to better illustrate the system design concept, the following sections will analyze various challenges encountered for this general design layout at the component level.

4.2.1 PCU and Laser Head Assembly

The laser system employed is a flash lamp pumped Nd:YAG pulsed laser. It is supplied by CONTINUUM Laser, model SL-I-20 (Surelite I-20 [164]). It consists of five basic components, namely laser bench optics, laser head, harmonic generator, electronics, and Power/Cooling Unit (PCU). A diverging lens assembly is installed right in front of the aperture to diverge the laser beam to an approximated 9.5° angle of half-diverging cone propagation. This assembly could be replaced with a divergent lens attached to a beam expander in future.

The laser bench consists of optical lenses, laser heads, electronic, and harmonic generator. A second harmonic generator is used to exert 532 nm from 1064 nm wavelength, with about 10 ns pulse length at preset 1 to 20 Hz frequencies. There is

an optional Surelite Separation Package (SSP) to direct the laser beams based on their wavelength. (Figure 4.6)

The PCU is the control of the laser system for power-up time, delays, pulse repetition frequency and Q-switch delays. It has a cooling unit to cool the laser rod and flash lamp by water/air forced convection. The power output from the laser (second harmonic 532 nm wavelength) is measured by using an OPHIR power meter [168] (PE50-BB-DIF-SH). The energy output is estimated to be about 0.143 Joule (J) for a Q-switch setting of 156 microseconds [162].

Figure 4.6 Laser Head & Diverter Assembly

For actual underwater application, the laser head and harmonic generator should be encapsulated in one package with compacted cooling devices, such as a Peltier [44] cooler, water cooler. In terms of the cooling problem, a diode pumped or semiconductor laser produce less heat compared to the current flash lamp pumped laser. This will reduce the system cost and inefficiency in terms of cooling system design consideration.

In terms of eye safe requirement, it is recommended to design the system based on various international standards, such as IEC 60825 part 1 to part 14[169], BSEN208:1999 [170] etc. As a rule of thumb, the energy per pulse, H_0 of a laser

system based on IEC 60825 for a Class 2 laser (400 – 700 nm in wavelength) design with fixed field of illumination (FOI, or angular subtense, α) can be roughly calculated as:

$$H_0 = 0.085 \tan^2(\alpha/2) \quad (4.3)$$

Equation 4.3 is derived from the Accessible Emission Limits (AEL) for an extended source with diverging angle higher than 6° . It is assumed that the transverse profile of the diverged beam is flat. For $\alpha=20^\circ$, H_0 is about 3 mJ/pulse, while for larger FOI ($\alpha=100^\circ$), H_0 should be less than 120 mJ/pulse. Thus, the current laser system is not eye safe for human access. For this project, the system computer and controls are isolated from the experimental area (the laser, the camera and the water tank) with a Venetian curtain. Thus, no human access is allowed to enter the scene when the laser is running.

4.2.2 Delay Generator

Figure 4.7 DG535, Delay Generator

The Delay Generator, DG535 is from Stanford Research System, Inc [46]. It is a delay generator capable of delivering up to 5 ps (picoseconds) resolution and about 60

ps of jitter. The minimum delay between input and output is 85 ns. The output has about a 2-3 ns rise time. Compared to other electronics in the system, DG535 is generally stable and accurate enough to generate camera gate input and frame grabber input signals. This unit can be replaced by using a high clock speed FPGA (up to 200 MHz is required).

4.2.3 Xybion Camera

The camera system consists of 2 parts, namely Intensified CCD Video Camera [166](ISG-250) and Video Camera Control Unit [165] (CCU-01). They are products from Xybion Electronic Corporation, which is known as ITT Industries Night Vision, after the acquisition of ITT Industries.

As shown in Figure 4.8, the Xybion ISG cameras are designed to incorporate a switchable Micro-Channel Plate (MCP) intensifier, solid-state imager, and Large Scale Integrated video circuits (LSIs). Generally, there are three frequencies needed to be synchronous with the laser pulses in order to range gate the RITP.

First, it is the gate opening time and gate duration. This has been heavily discussed in this thesis (Chapter 5 & 6).

Second is the CCD scan rate, it could be line transfer, frame transfer, full frame transfer, time delay and integration (TDI) etc. The CCD charges are normally shifted to the register before the beginning of the each individual frame (odd and even) in just a few microseconds. This timing is not critical for nanosecond gate time as there are milliseconds of time slack for this timing to coincide with each other. There is only one over thousand probabilities to scan the CCD while the MCP is open. However, there is still a risk to capture empty frame if the scanning is coincidentally registering the empty wells after the CCD wells are cleared. The CCD arrays are cleared immediately after the charges from even frame (the second frame of an interlaced video stream) transferred to the register. This problem could be avoided by taking images only before the CCD wells are cleared.

Third is the video output rate. The video output rate can be set in frame or field mode. The output is RS-170 monochrome standard with up to 30 (frame mode) or 60 (field mode) frames per second. The image inhibit feature allows control of multiple frame integration and asynchronous imaging (video output timing).

The Xybion camera has an adjustable camera gate (shutter), range from 5 ns to 20 mille-seconds (ms) according to the manuals. However, the minimum gate duration has been empirically found to be about 14 ns (measured from the gate readout). The amount of energy entering the camera to form an image can be controlled by lens iris or aperture and the intensifier. The intensifier acts as a camera gate and gain control before the electrons reaching the output phosphor screen. Generally, this assembly is considered as a Second Generation (Gen II) image intensifier. It consists of a vacuum sealed unit made up of metal and ceramic body parts, input and output windows, and a MCP. The intensifier is optically coupled to the imager array by a fibre optic minifier that reduces a 1-inch intensifier format with 30 ± 2 line pairs per mm (lp/mm) at the centre and 28 ± 2 lp/mm in the corner to 2/3-inch format of the imager (CCD array).

Figure 4.8 Xybion camera

Functionally, the tube body of the Generation II intensifier is a combination of tube elements, such as photocathode, MCP, and output phosphor screen. Appropriate voltages are applied between the various tube elements to multiply the electrons from

one element surface to the other with minimum electron spread spatially. The fast shutter function is implemented by switching the low voltage between the photocathode and MCP on and off. Hence, the actual gating effect is in fact an amplification of photon effect on the MCP amplifier itself. The gate turns off when the amplifier is switched low, while it is on when the amplifier is switched high.

Therefore, by operating the intensifier as an optical shutter between the lens and the imager with shorter gate duration, the intensifier could act as a camera gate with nanosecond speed. The actual sensitivity is affected by the gate duration as [166]:

$$S_f = \frac{S_i T_g}{T_f} \quad (4.4)$$

S_f is the final sensitivity (foot candle, fc). S_i is the camera's ungated sensitivity, T_f equals the readout rate of the camera (16.67 ms for field mode, 33.33 ms for frame mode), and T_g is the camera's gate duration in ms.

4.2.4 Camera Control Unit (CCU)

The CCU complements the ISG-series camera by acting as an enhanced camera control panel (Figure 4.9). One of the important features on the camera control unit is the external trigger knob. It offers the camera trigger in VD (Vertical Drive), HD (Horizontal Drive), External Triggering and By-pass modes.

For this project, by-pass mode is used. The gate signal from the DG535 is by-passed through the CCU to the camera, allowing the camera gate time to be synchronous with the lasing events. Besides, it has manual gain power function that will vary the light gain of the camera's image intensifier by changing the voltage across the intensifier MCP. Since the cameras might be damaged if too much incoming light energy enters the CCD arrays, all Xybion intensified cameras are designed to automatically reduce the intensifier light gain in the event that the input light level rises too high. Thus, the knob actually controls the upper limit to which the camera gain can go. There are some automatic gain controls, like ABC (peak/ average + level), and the control of exposure time correspond to video signal amplitude. However, only manual gain control below the saturation limit is used in this project.

Figure 4.9 CCU control unit

One of the challenges present in this project is the non-linear characteristic of the effective camera gate duration in ns speed. The input gate duration from the DG535 might be longer than the actual camera gate duration, even though it is in the by pass mode.

From current observation, the shortest input gate duration from the DG535 is about 14 ns in order to generate a good image response. The camera gate readout is basically reflecting the input gate time from the DG535, but the actual effective camera gate time is not in proportion to the input. This situation is even apparent when images are taken in higher turbidity. As the light level is attenuated by turbid water, the effective gate time seems to be reduced even though the input gate time is still the same. It is believed that the effective camera gate time is a Gaussian profile rather than a square profile with instantaneous fall and rise time.

Another problem encountered is the blooming/saturation effect on the CCD array, due to high incoming light or high gain applied. To avoid this problem, at least for the time being, the image taken should be always below the saturation level.

4.2.5 Photo Detector

The photo detector used is produced by Newport modelled 818-BB-20[147], as shown in Figure 4.8. It basically consists of free-space, small area Silicon detectors, with rise times less than 350 ps. It has a built-in bias supply consisting of standard 3 V lithium cells and a BNC connector output, to be terminated into a 50 ohm resistor. The photo detector is sensitive from 300 nm to 1100 nm wavelength region. It is placed as close to the camera as possible, to measure the RITP received by the camera.

4.2.6 Frame Grabber, Oscilloscope, and Attenuation Meter (AC9)

A frame grabber from Matrox Imaging [45] is used. It is the Meteor II card with complete software support of Graphical User Interfaces (GUI, Intellicam®) and libraries for C++ environment. It is set to RS-170 standards, hardware triggered by the DG535. Besides, the SNAZZI III [167] interface provides USB2 connection to transfer the RS-170 video to a personal computer with video capturing software (Movie Mills®). This has allowed image sequences to be captured for real time and for demonstration purposes.

The oscilloscope used is from Tektronix, Model TDS3054 [171], as shown in Figure 4.1. It is a digital phosphor oscilloscope with up to 500 MHz bandwidth. Its input dynamic ranges from 1 mV/division to 1 V/division. The sampling rate can be set up to 5 giga-samples/second.

The attenuation meter (AC9) is provided by WetLabs [163]. It is complemented with software to compute and store the data from AC9. This is one of the most popular

attenuation meters used by oceanographers to study sea optical properties [172]. Detailed calculations to obtain absorption and attenuation coefficients for various wavelengths are shown in the manual. Each water condition is measured twice, one is before the experiment and the other is after the experiment for any water condition used. This is to ensure that the water condition is maintained throughout the experiment. Normally, a more stable reading is found for the measurement after the experiment. Hence, each water condition simulated for experiments should only be used when the AC9 produces steady readings.

4.3 The testing target in simulated water condition

Since the project scope is focusing on short distance imaging system and also due to the limited space in the laboratory environment, a 3 m (length) x 1 m (height) x 1 m (wide) water tank is built. (Figure 4.1)

The turbid water conditions have been prepared using different approaches by various researchers. In 1993, Mullen et al. [173] had set up a simple and inexpensive method with plastic optical fibre system to simulate the backscattering effect of various seawater conditions. Unfortunately, the system was unable to carry image information on return. Thus, it is not suitable for imaging application.

Some of the researchers used real seawater to simulate the turbid condition. Heckman [30] used natural turbid water in his experiments, and filter the water to achieve the required turbidity in 1969. Gilbert et al. [174] studied the major difference between the laser and ordinary incoherent light in lake waters.

As an alternative, most researchers used chemicals mixed with fresh water to simulate the actual turbid water in laboratory conditions. Witherspoon et al. [37] and Edward et al. [175] used Maalox [176] (mixture of aluminium and magnesium hydroxide) as a scattering agent in their experiments. It has been perceived as a reasonable surrogate for most types of ocean water [177], [178]. For this project, a similar chemical is used to simulate the turbid seawater condition in fresh water with Mylanta®. The Mylanta® [179] is also a mixture of aluminium hydroxide, magnesium hydroxide, and some other minor non-active ingredients.

Most of the researchers have used their own resolution targets, which consist of different sizes of bars to represent different spatial frequencies, and only black and white colours were used. Besides, they also use common items such as vehicles, steel

plates, and drums to create some isometric views. The target range can be as far as 60 m for bathymetry study, or as close as 1 m for range-gated imaging researches.

In early 90s, Fournier et al. [34] and Chu et al. [75] used a standard air force target in their underwater imaging experiment. Since then, the United State Air Force (USAF) [180] standard target becomes a popular testing target for various researchers [19], [20]. Similar spatial resolution targets are used in this project (as shown in Table 4.1). The USAF target has rectangular bars resolution orientated horizontally and vertically which will allow spatial frequency analysis in two dimensions. It consists of various spatial frequency arrangements ranging from 6 mm/cycle to 100 mm/cycle. These are low frequency compared to the resolution of the CCD arrays. Hence, the system can be approximated as linear and shift invariant.

Reflective (or specular) targets will create a concentrated reflection to the camera direction. It may distort the image quality due to CCD array saturation and uneven reflection from the target at different angles. Therefore, the ideal target should produce no specular reflections from the illuminating light. It is hence suggested to use cloth or paper materials, where their surfaces are not polished. Then, the reflection of light will be evenly distributed according to the Lambert's Cosine Law of Intensity.

4.4 Quantified Image Quality Index

It is known that the quality of an underwater imaging output can vary dramatically depending on system design and control parameters [10]. Thus, a common scale of image quality or interpretability is needed as a basic measure of the information content of the output images and the expected performance that they provide. By comparing the computed measures of range-gated and non-gated images, this section aims to quantify the performance of our range-gated imaging system in increased water turbidity.

As explained in Section 2.1.4, a selected image quality index should be able to reflect the level of scattering noise reduction of an image output. Thus, three related image quality assessment indexes are selected to quantify the image quality. They were selected primarily due to their recent positive reports [10], [181], [182] on measuring the performance of turbid medium imaging system, but in different domains.

The first measure is the Modified Fidelity (*MF*) [10] that represents the normalized absolute difference of amplitude. The second measure is the Modified Strehl Ratio

(*MSR2*) [181]. It was first being used to measure adaptive optics system performance by Brigantic et al. in 1997. This metric is a measure of the Modulation Transfer Function (*MTF*) of an image in a scattering medium. The third measure is the Contrast-to-Noise Ratio (*CNR*) [182] computing the histogram stretch of the image in turbid medium. It is used by Xiang et al. [182] in a tissue imaging system. Generally, these metrics are considered as a measure of similarity between the idealized and the derived images in the spatial domain (*MF*), spatial frequency domain (*MSR*) and histogram domain (*CNR*).

Most of the underwater imaging systems are evaluated by using 2-dimensional greyscale images of USAF (United State Air Force) targets. For laboratory testing conditions, the targets and the imaging system can be fixed in a water tank.

By increasing the concentration of Mylanta into the water medium to simulate the turbid environment while maintaining all other factors, the image quality is gradually degraded only from the turbidity factor. This will enable the system design to concentrate only on reducing the degradations with either hardware upgrading or optimization stage. Therefore, the computed measures are needed to correlate with the scattering effect appearing in the output image. Thus, the image quality indexes are introduced as performance measures of imaging systems or image enhancement techniques.

The Modified Fidelity (*MF*) reflects the difference between the investigated (degraded) and idealized (reference) images in the sense of normalized least square error. However, it could not discriminate the scattering effect from any other image impairments. Hence, careful control of the testing environment is required before the evaluation methods could be applied. It is recommended to measure the fidelity among the same set of images with constant geometrical parameters and background effects. The *MF* index is defined as,

$$MF = 1 - \frac{\sum_{i=1}^N \sum_{j=1}^M \left[\frac{I'(i, j)}{I'_m} - \frac{I(i, j)}{I_m} \right]^2}{\sum_{i=1}^N \sum_{j=1}^M \left[\frac{I(i, j)}{I_m} \right]^2} \quad (4.5)$$

where $I'(i, j)$ and $I(i, j)$ are the pixel values of the investigated and idealized images, respectively, for the pixel located at row i and column j . I'_m and I_m denote the mean

pixel value of investigated and idealized images. N and M identify the number of rows and columns of the images.

$MSR2$ is modified from the original Strehl Ratio (SR); the numerator of the SR is the integration of the image MTF up to the noise effective cut-off (NEC) frequency. In this case, the NEC frequency ($f_{NEC} = 0.886f_{max}/2$) is defined as 0.886 times half of the Nyquist frequency (f_{max}) of the image. The $MSR2$ is defined as,

$$MSR2 = \frac{\int circ(f / f_{NEC}) MTF_{sys}(f) df}{\int circ(f / f_c) MTF_{dl}(f) df} \quad (4.6)$$

$$circ(f / f_c) = 1, \quad |f| / f_c \leq 1; \quad 0 \text{ otherwise} \quad (4.7)$$

$MTF_{sys}(f)$ is the MTF of the testing image. $MTF_{dl}(f)$ is the modulation transfer function of the diffraction limited image. In this thesis, it is assumed that the ideal image is taken in clear water conditions. f represent spatial frequencies and f_c is assumed to be half of the Nyquist frequency of ideal image.

The Contrast-to-Noise Ratio (CNR) is derived from the Contrast Radius of Gyration (CRG). The CRG is calculated from the contrast stretching of the testing image itself without the ideal image as reference. Therefore, it is defined as

$$CRG = \sqrt{\frac{\int_0^P (p - p_m) h(p) dp}{\int_0^P h(p) dp}} \quad (4.8)$$

$$p_m = \frac{\int_0^P p h(p) dp}{\int_0^P h(p) dp} \quad (4.9)$$

From an investigated image, p is a grey level with a range of $(0, P)$ and $h(p)$ is the corresponding grey level histogram. p_m is the mean value of the grey level. The CNR is formulated as,

$$CNR = \frac{2 \times CRG}{\sigma_{noise}} \quad (4.10)$$

$$\sigma_{noise} = \left\{ \frac{\iint [I'_0(i, j) - I_0(i, j)]^2 dx dy}{M \times N} \right\}^{1/2} \quad (4.11)$$

$$I'_0(i, j) = I'(i, j) - I'_m; \quad I_0(i, j) = I(i, j) - I_m$$

The *CNR* considers the noise as the energy difference between the tested image and ideal image. It is defined as the ratio of contrast gyration diameter to noise energy.

4.5 Performance Evaluation Of Range-Gated Imaging System

In this section, the main objective is to quantify the improvement of underwater images from non-gated to gated images. It is recommended to compute the indices among the same set of images with constant geometrical and background effects. By keeping the target fixed in the camera field of view along the experiment, temporal and spatial distortions are minimized. Background noise and camera noises should be kept constant for all images taken for comparison. Image manipulation processes should be kept to minimum. The only desired changes in this image quality evaluation are the turbidity of seawater and camera control parameters, such as gated and non-gated configurations, while other hardware parameters are maintained.

Figure 4.10 and Table 4.1 show the respective image captured in non-gated and gated condition at three turbidity levels. Target range is about 3 m. For all indices, the gated image in 1.5 AL (low turbidity, $C = 0.5$ /m) rated highest whereas the non-gated

image in 5.3 AL (high turbidity) rated the lowest. In order to compare them within a dynamic scale, all indexes are normalized from 0 (non-gated, $C = 1.8 / \text{m}$) to 1 (gated), as shown in Figure 4.10. The *CNR* does not correlate with the *MSR2* and *MF* indexes because it shows the gated turbidity level image is better than the non-gated clear water image (not reflected in other indicators, including naked eye observations).

Turbidity level	Non- Gated Image	Gated Image
Low turbidity, Level 1 (1.5 Attenuation length, AL)
Medium Turbidity , Level 2 (3.5 AL)
High Turbidity, Level 3 (5.3 AL)
Table 4.1. Comparison of Non-gated and Gated Images in 3 levels of turbidity. The black spot on the images is due to accidental damage caused by a sharp laser beam.		

In terms of subjective evaluation, the *MSR2* and *MF* are well agreed with naked eye observations. Generally, they all show range-gated images have at least 40% (calculated based on the *MF* value) higher quality than non-gated images in level 3. The potential of range-gated systems is believed to be better if fine-tuning of the gate timing is considered. This concept is introduced by Witherspoon et al. [37] and in Chapter 5.

4.6 Chapter Summary

This chapter basically reports the NTU range-gated imaging system set up in a laboratory condition. The performance is evaluated quantitatively with the experimental procedure proposed by Tan et al. [10]. The image quality metrics show

about 40% of improvement compared to non-gated configuration at higher turbidity level. In order to evaluate various optimization techniques available to fine-tune the performance of range-gated imaging system, it is first set up as the engineering test bed for actual system design in future. Each component of the system is featured and documented; this has provided enough information for appropriate equipment selection, justified by the application requirements.

Figure 4.11 summarizes most of the fundamental features of a proposed range-gated imaging system needed for URV applications. The programmable control unit needs to have up to a few nanoseconds of time resolution to adjust the gate opening time. For remote operation, it should possess basic image enhancement, fusion, and compression features that could reduce the burden of the communication channel for raw image data. The interfaces convey information among the modules as well as with human operators. The human interface should be typically a Graphical User Interface (GUI) and the surface-underwater link should enable long distance signal transmission.

The overall system design should consume the least amount of energy possible. For offshore oil and gas operation, it must be compliant with various safety standards,

such as intrinsically safe, explosion proof, and water tight or purging of humidity. There are various industrial standards that have emphasized detailed calculation and design of power supplies, such as EN50014 [183], EN50018 [184] etc. The system enclosure should be water tight to underwater pressure. Various standards are available to direct the design steps, such as BS6362 [185], BS5380 [186] etc. The laser system should also be inaccessible to untrained personnel based on the relevant industries standards, especially in the underwater condition. It should be noted that the mounting of the lenses and optical component should be translationally and rotationally adjustable (or in-axis) by trained personnel in laboratory condition, this will allow more accurate and clear imaging capability in different underwater environments.

The laser system and the camera system should be flexible enough where the laser pulses, camera gate time, camera scan rate, and video output are synchronous under one centralized control. Figure 4.12 shows the experimental setup. The basic framework of underwater range-gated imaging system is basically determined with current observations. In order to evaluate the performance of this system, three image quality indexes are selected to compute the quantitative fidelity between the images captured in turbid condition and the reference image in clear water. At least 40% improvement is achieved for current range-gated imaging system in high turbidity level (calculated based on the MF values at 5.3 AL).

Despite the system improvement in terms of hardware upgrading (as explained in Section 1.2.2 & 1.2.3), the objectives of this project are to further optimize or enhance the system performance within the existing hardware configuration (as stated in Section 1.3). This has motivated the following chapters to analyze the backscattering phenomenon analytically and also to further optimize the system performance in terms of gate timing and image processing.

CHAPTER 5

BACKSCATTERING NOISE ANALYSIS WITHIN REFLECTED IMAGE TEMPORAL PROFILE (RITP)

This chapter reports the analytical work for range-gated imaging systems in the time domain. It formulates the backscattering noise within the actual RITP as a function of pulse length and gate timing. The variation of this noise effect has affected the Signal to Backscattering Noise Ratio (SBR). This analytical formulation explains the feasibility of the tail-gating concept. Further analysis clarifies how shorter pulse length and gate duration can improve range-gated image quality from the perspective of backscattering noise.

5.1 Introduction

It is well known that by using shorter pulse length and/or gate duration, the image quality in turbid water medium is expected to be better. Various numerical and experimental results [39], [38], [81] have shown this effect successfully. However, to the author's knowledge, there is no existing analytical model considering the backscattering noise as a function of the outgoing pulse length and the correct gate timing for opaque target effect, within the target irradiance (actual RITP, Reflected Image Temporal Profile). This thesis proposes a formulation that models the backscattering noise as a convolution with a fixed upper-limit due to an opaque target; this is a modification of Falk's LIDAR equation applied to an opaque target effect. Further analysis shows this formulation successfully explains the significant improvement of the Signal to Backscattering Noise Ratio (SBR) for range-gated imaging systems in various scenarios, such as delayed gate timing, shorter gate duration only, shorter pulse length only, or both.

Compared to most of the backscattering noise returning prior to the arrival of target irradiance at the aperture, it is true that most of the backscattering noise reflected back to the camera has been filtered out from the camera at the target gating. Thus, most analytical range-gated imaging models assume there is no variation of backscattering effects [141], [143] within the reflected pulse of target irradiance (actual RITP). Witherspoon et al. [37], however, predicted that *“by timing the gate to close so as to image the target tail region of the transmitted laser pulse, any backscatter due to the*

transmitted laser beam in the intervening water volume will not be recorded by the camera". On the contrary, McLean et al. [39] showed that (neglecting the backscattering effect) front RITP gating had better image quality than tail RITP gating. With this formulation, the variation of backscattering noise (due to fixed upper-limit convolution effect at tail RITP region) is predicted and improvement of the SBR towards tail RITP region is shown. This theoretical observation correlates well with Witherspoon's observations and subsequently has been verified by the Monte Carlo simulation and experimental results in this chapter.

Moreover, this formulation shows that shorter gate durations may not necessarily produce better SBR unless it is gated at higher SBR interval, such as in the tail RITP region.

Finally, shortening Gaussian pulse lengths results in reduction of total backscattering noise within the actual RITP, even with the same amount of energy per pulse, i.e. this formulation lead to the correction of the backscattering noise calculation and explains analytically why the SBR is higher for shorter pulse lengths used in range-gated imaging systems.

5.2 Backscattering Noise within RITP

In underwater range-gated imaging systems, the receiver is adjacent to the light source while the underwater target is behind the scattering medium. Thus, the Reflected Image Temporal Profile (RITP) is observed as a super-position of a single target reflection and the backscattering noise in the time domain. For an infinite length (impulse input) light pulse exerted into the medium, the backscattered energy at the receiver is modelled using a Temporal Point Spread Function [145] (TPSF), which represents the reflectance from the medium. The RITP is formed when the TPSF and target irradiance convolves with an approximately Gaussian [146] pulse produced by the illuminator (light source). This was explained in Chapter 3.

In order to investigate the variation of total backscattering noise within the RITP, Equation 3.2 is simplified as

$$P_{BSN}(t) = \sum_i P_i(t) \quad (5.1)$$

$i \in \{\text{DBD, GBD, DBG, GBG, DBM, GBM, MBD, MBG, MBM}\}$ where i denotes different categories of photon groups at time t (refer to Section 3.2).

For a given semi-infinite medium, the backscattering elements in any given time slice are the convolution between the backscattering TPSF and the half-distance of the on-going laser pulse. Without considering the geometrical effect and forward scattering issues, Falk et al. [108] defined the backscattering noise, as:

$$P_i(t') = \int_{v(t-t_0)/2}^{vt/2} S_i(r) P_0(t' - 2r/v) dr \quad (5.2)$$

The laser emits a pulse with power profile $P_0(t)$ starting at $t = 0$ and ending at $t = t_0$. The kernel of the convolution integral function $S_i(r)$ is the TPSF of each component, where $i \in \{\text{DBD, GBD, DBG, GBG, DBM, GBM, MBD, MBG, MBM}\}$, and v is the light speed in the medium.

A similar approach based on Equation 5.2 is considered for range-gated imaging systems. For a laser pulse sent to an underwater target in turbid conditions, the photons are assumed to have constant speed and travelling through virtual linear distance, $r = vt/2$. The returning pulse length will be stretched due to the longer photon transportation path in multiple scattering processes, where $\langle \tau \rangle$ represents the mean multi-path time. If the emitted pulse with temporal profile $P_0(t)$, hits an opaque target, and all the energy is either absorbed or reflected at the target, then the convolution process of backscattering effect will terminate at target distance, r_0 . This effect is well understood. However, in order to establish a formulation to predict this phenomenon, a fixed upper-boundary condition due to the opaque target is introduced. Equation 5.2 can be rewritten as

$$P_i(t') = \int_{v(t-t_0)/2}^{vt/2} S_i(r) P_0(t' - 2r/v) dr \quad \text{for } t \leq (2r_0/v + t_0 + \langle \tau \rangle) \quad (5.3)$$

Assuming pulse stretching is negligible for short target distances (or less than 10 attenuation lengths, AL [150], [154]) in turbid seawater, $\langle \tau \rangle \approx 0$; then $P_i(t) = 0$ for $t > (2r_0/v + t_0)$.

With an opaque target, this formulation describes the backscattering noise as a function of TPSF of the medium, outgoing pulse profile, pulse length t_0 , and time t . Direct interpretation of this function implies that backscattering noise is linearly

proportional to the outgoing power $P_0(t)$ and $S_i(r)$, but nonlinearly related to pulse length. The backscattering noise is also affected by the fixed upper-limit at $t > (2r_0/v)$, i.e. if the lower virtual limit r as time function of $v(t-t_0)/2$ is approaching $(2r_0/v + t_0)$, then $P_{BSN}(t)$ reduces. Based on Equation 5.3, it is predicted that the backscattering noise is reduced at the tail end of RITP compared to the front of Actual RITP region. It will be discussed in the following sections.

For single point source coinciding with the receiver position, the backscattering results obtained from a semi-infinite scattering medium can be described by Equation (5.1) and (5.3) as

$$P_{BSN}(t') = \sum_i \int_{v(t-t_0)/2}^{vt/2} S_i(r) P_0(t' - 2r/v) dr \quad \text{for } t \leq (2r_0/v + t_0 + \tau) \quad (5.4)$$

$i \in \{\text{DBD, GBD, DBG, GBG, DBM, GBM, MBD, MBG, MBM}\}$ where i denotes different categories of photon groups at time t .

For underwater imaging systems, the laser is normally diverged into a wider FOI (Field of Illumination). The receiver could be a camera with non-pin hole aperture area and FOV (Field of View). Thus, the multiple scattering components, such as: P_{DBM} , P_{GBM} , P_{MBD} , P_{MBG} etc, are believed to have higher contributions to the total backscattering noise.

In order to better understand the variation of $P_{BSN}(t)$ within the Actual RITP, the Monte Carlo method is used to simulate the complex illuminator-receiver configuration for RITP. This simulation is coded as MCRITP (As described in Chapter 3). The TPSF is convolved with $P_0(t)$ in a Gaussian function profile [146] to simulate the actual backscattering noise of the underwater imaging system in a given turbid medium. The outgoing Gaussian profile is defined as

$$P_0(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(t-100)^2/\sigma^2} \quad (5.5)$$

The Gaussian function (Equation 5.5) is modelled based on experimental data (Chapter 3) with central axis at 100×0.1 ns/data point = 10 ns, and $\sigma = 3$ ns.

In order to quantify the backscattering noise of a range-gated system, the following figures are used to run the simulation. For five million photons, it takes averaged 90 minutes simulation time. For a perfect irradiance receiver in semi-infinite media, the

receiver aperture is 0.2 meter in diameter and FOV at 10° half angle ($\alpha = 20^\circ$) based on system specifications (Chapter 4). Besides, three attenuation coefficients, C and their respective absorption coefficients, a are used to run the simulation (based on actual experimental measurement in Chapter 3). This aperture size is set large enough to avoid significant statistical error for the 5 million photons simulated. The FOI of a point source is set to 10° half angle (Chapter 4), with about 6 ns Full Wave Half Maximum (FWHM) temporal length as described by Equation 5.5.

As an example, two simulated results are compared to illustrate the convolution effect owing to the opaque target model with and without a fixed upper-limit case. With a fixed upper-limit condition at a virtual 3 meters target distance, all photons travelling beyond the target distance will be truncated. Without a fixed upper-limit condition, all photons are free to travel for all positive distance z , until they fall into the aperture area within the FOV. Figure 5.1 shows the convolved results of MCRITP and Gaussian function (Equation 5.5). The time axis tracked the TPSF from the initial propagation time of the front end of the input pulses. For the fixed upper-limit condition, the actual backscattering noises (thick lines) are expected to be less than the non-fixed upper-limit case (thin lines) from 27 ns (assuming $v = 2.22 \times 10^8$ m/s) onwards. However, the pulse stretching effect has shifted the thick and thin line separation for about 8 ns (from $C = 0.86$ /m up to $C = 2.46$ /m).

In conclusion, the separation between the fixed upper-limits case (Equation 5.3 & 5.4) and non-fixed upper-limits case (Equation 5.2) in Figure 5.1 result from a sharp reduction of backscattering effect when the transmitted pulse hits an opaque target. This has subsequently resulted in a variation of SBR in the later stage. This effect is mathematically predicted and clarified in Equation 5.3 and 5.4.

Compared to the non-fixed upper-limit case, the $P_{BSN}(t)$ for the fixed upper-limit case is at least 65% less towards tail RITP region at about 50 ns in higher turbidity level ($C = 2.46$ /m). It is more than 100 times reduced in lower turbidity level ($C = 0.86$ /m). This has shown that the fixed upper-limit could reduce the backscattering noise significantly compared to the non-fixed upper-limit case; this phenomenon is modelled as Equation 5.4.

5.3 Target Signal and Signal Scattered Noise

In order to calculate the reflected signal of a seabed target, Ronald et al. [122], [123] established a simple analytical form to illustrate bottom return waveforms in shallow clear water when the transmitted pulse profile is known. The target signal can be modified from their analytical results as

$$P_S(t) = \sum_i P_i'(t) \approx [P_{target}(\zeta) \otimes P_0(t)] \quad (5.6)$$

$\zeta = r_o + v\tau/2$. $\otimes$ represents the convolution of $P_{target}(\zeta)$ and $P_0(t)$ over τ .

$i \in \{\text{DTD, DTG, GTD, GTG, MTD, MTG}\}$ where i denotes different categories of photon groups at time t .

In this thesis, $P_{target}(\zeta)$ represents the total impulse response function of each target signal component ($P_i'(t)$, indexed from DTD to MTG). $P_{SMM}(t)$ contains highly scattered reflected photons that have lost the original target reflection properties (such as location, orientation of the photon). For short target distances, $P_{SMM}(t)$ is assumed to be negligible compared to the backscattering noise within the range of turbidity levels shown in this chapter.

The Monte Carlo simulation has been run (five million photons, averaged 90 minutes simulation time) for the system specifications used in Figure 5.1 with Lambertian target reflectivity equal to 1.0 (100%) and convolved with Equation 5.5. As shown in Figure 5.2, the RITP curve and the target reflected signal, $P_S(t)$ (within FOV) are

plotted for increased turbidity. The target signal forms a normal distribution centred at around 40 ns for $C = 1.91$ /m and at around 38 ns for $C = 0.86$ /m. The Signal to Backscattering Noise Ratio (SBR) is expected to be higher when the total RITP energy converges with the target signal energy at the tail region. The SBR for $C = 1.91$ is less than 1 because of the receiver diameter is set to 200 mm, which is more susceptible to backscattering noise than the target signal.

5.4 Signal To Backscattering Noise Ratio within Actual RITP

The Actual RITP is defined as the interval of RITP that carry target reflected photons. A typical range-gated imaging system has its gate width equal to the Actual RITP to integrate as much target bearing photons as possible to achieve the highest Signal to Backscattering Noise Ratio (SBR) [28], [187]. Supposing the camera gate is open at t_2 , and closed at t_1 , the corresponding backscattering noise integrated by the camera could be defined as

$$E(t_1 - t_2) = \int_{t_2}^{t_1} P_{BSN}(t') dt' = \int_{t_2}^{t_1} \int_{v(t-t_0)/2}^{vt/2} S(r) P_0(t' - 2r/v) dr dt' \quad (5.7)$$

$$\text{for } t \leq (2r_0/v + t_0 + \langle \tau \rangle)$$

For photons reflected back to the camera aperture, the overall target signal integrated by the camera from t_2 to t_1 is

$$E'(t_1 - t_2) = \int_{t_2}^{t_1} P_s(t) dt \quad \text{for } (2r_0 / v + t_0 + \langle \tau \rangle) \geq t \geq (2r_0 / v) \quad (5.8)$$

Subsequently, the Overall Signal To Backscattering Noise Ratio (*OSBR*) could be formed as

$$OSBR = \frac{E'(t_1 - t_2)}{E(t_1 - t_2)} = \frac{\int_{t_2}^{t_1} P_s(t) dt}{\int_{t_2}^{t_1} \int_{v(t-t_0)/2}^{vt/2} S(r) P_0(t' - 2r/v) dr dt'} \quad (5.9)$$

The variation of SBR within the RITP, the Instantaneous Signal To Backscattering Noise Ratio (*ISBR*) is defined as

$$ISBR(t) = \frac{E'(t)}{E(t)} = \frac{P_s(t)}{\int_{v(t-t_0)/2}^{vt/2} S(r) P_0(t - 2r/v) dr} \quad (5.10)$$

The variation of the *ISBR(t)* indicates better signal to backscattering noise ratio if the gate timing is selectively open at the interval of highest *ISBR(t)*.

5.4.1 Gate timing delay

The *ISBR* (Figure 5.2) is plotted from 30 ns to 45 ns interval in Figure 5.3. The central line of target signal distribution (shown in Figure 5.2) is labelled as the middle point of actual RITP. The highest *ISBR* values calculated show a parabolic curve with its peak centred towards the tail RITP region respectively. These *ISBR(t)* curves imply the gate timing triggered towards the tail RITP region generally produces better image contrast to backscattering noise than for the front RITP region [37], qualitatively. However, this still depends on the ability of camera to pick up a weaker target signal and produce better image quality. In conclusion, it shows that even the target signal is reducing in the tail RITP region, but it may not necessarily result in lower SBR.

The *OSBR* response in Figure 5.3 could be explained based on Equation 5.9. If the gate duration is fixed and delayed towards the tail RITP region, t_2 approaches the fixed upper-limit $2r_0/c + t_0$. Then, $E(t_2 - t_1)$ or the integrated backscattering energy will be lower because $P_{BSN}(t)$ dissipates tremendously after $t > 2r_0/c$. With a higher percentage of $P_s(t)$ ($P_s(t)$ does not dissipate as much as $P_{BSN}(t)$) towards the tail

RITP region, higher *OSBR* is achieved. With enough camera sensitivity to pick up the dissipated target signal at the tail RITP region, better quality range-gated images are expected. This observation has been experimentally verified in Figure 5.4 and Table 5.1.

For the same problem, Witherspoon et al. [37] and McLean et al. [39] have opposite observations from their experiments. Witherspoon stated (based on their experimental observations) that tail RITP gated images produce better image quality with less backscattering noise. McLean et al., however, shows that front RITP gated images are better (based on Monte Carlo simulation without considering the backscattering noise within the target irradiance itself). However, none of them offers analytical insight into the problem. This project provides analytical tools to predict the image quality by using the *OSBR* concept. Apparently, the *OSBR* is highest if the region of highest *ISBR* is integrated. From Figure 5.3, the gate timing should be shifted to centre at around 42 ns, which is the tail region of RITP.

It should be noted that the values of simulated SBR (*ISBR/OSBR*) are generally smaller than one. However, the camera should achieve SBR higher than one to produce clear images. This discrepancy might be due to the simulated aperture

diameter of 200 mm, which is wider than the actual camera lens aperture diameter (less than 5 mm). For monostatic or close to monostatic cases, increasing/decreasing the aperture will not proportionally increase/decrease the noise and target reflected signal. It is because the target reflected photons with minimum degree of scattering from its original path will tends to shows PSF in small angle approximation (very sharp and narrow distribution in spatial domain). While backscattering noise normally exhibit Gaussian or diffusive PSF at the aperture area. Thus, increase/decrease the aperture will not proportionally magnify/reduce the backscattering noise and reflected target signal. In this case, the increased aperture allows a higher portion of backscattering noise energy to be accumulated in the receiver aperture. In terms of time domain data point density, larger simulated aperture will increase the number of $P_{target}(t)$ data points temporally.

The aperture size and number of photons have been increased with a trial and error method for numerous runs to minimize the statistical error of $P_{target}(t)$ in our simulation. Subsequently, the convolution of the $P_{target}(t)$ with $P_o(t)$ achieves the smooth curve with enough sampling points at 200 mm of aperture diameter for the 5 millions photons simulated. Thus, it has caused the calculated SBR to be less than 1.0. In order to rectify this problem, the Zege et al. [79] model is adopted to correlate the aperture area linearly with the backscattering noise energy received in this simulation. The target signal basically consists of a forward peak light beam propagated back to the receiver that has not reduced linearly with the receiver size. It is assumed to maintain its signal energy even with smaller aperture diameter. By scaling down the backscattering energy received to the actual camera aperture (5 mm diameter), the SBR recalculated is much higher than unity. These results have enabled the clear images taken in the turbidity shown in Figure 5.3. Most importantly, the major concern of this analysis is to compare the relative quantities of SBR within the RITP instead of the absolute values.

In order to verify image quality variation within the RITP, the range-gated imaging system described in Chapter 4 has been used to capture various temporal energy bands within the Actual RITP. First of all, the gating duration is minimized. Adequate camera gain is monitored to fine-tune the camera gate opening time towards the tail of the RITP in order to capture visible target image. The same approach would be used

to capture images at Middle RITP and Front RITP (by switching on the camera gate 4 to 6 ns earlier) for comparison.

Although the images captured in Table 5.1 and Figure 5.4 are noticed to have differences in quality with subjective rating, quantitative image quality measures would still be needed in order to compare image quality of the range gated imaging system more objectively.

Earliest Delay (ns)	Latest Delay (ns)	C , 1/m	a , 1/m	Gate opening time	Duration (ns)	MF	Recalculated $OSBR$
13	37	1.38	0.24	Tail RITP 37	14	0.811	8.3×10^2
				↑	31	0.840	1.3×10^3
				↓	25	0.819	9.4×10^2
				↓	19	0.790	2.1×10^2
				Front RITP 13	14	0.747	48
20	34	1.82	0.31	Tail RITP 34	14	0.798	1.0×10^3
				↑	30	0.796	5.9×10^2
				↓	25	0.753	2.4×10^2
				Front RITP 20	14	0.717	64
25	32	2.07	0.36	Tail RITP 32	14	0.766	2.7×10^2
				↑	27	0.766	80
				Front RITP 25	14	0.700	48

Table 5.1 Camera Gated Opening Time for range-gated imaging system in increased turbidity

Besides the experimental results, the Monte Carlo approach is also used to support the observation and verify Witherspoon's prediction. MCRITP was run for each Attenuation Meter (AC9) measurement. The results have been convolved with the Gaussian output function, as described by Equation 5.5. The FOV and FOI have been set to 10° half-cone angles and 200 mm receiver diameter. $OSBR$ from Equation 5.9 is recalculated, scaling down the receiver diameter to its actual value, 5 mm. Signal scattered noise data within the small FOV and short target range are neglected.

$C = 1.38/\text{m}$	$C = 1.82/\text{m}$	$C = 2.07/\text{m}$

Gate Delay = 37 ns, $MF=0.811$	Gate Delay = 34 ns, $MF=0.798$	Gate Delay = 32 ns, $MF=0.766$

Gate Delay = 31 ns, $MF=0.840$	Gate Delay = 30 ns, $MF=0.796$	Gate Delay = 27 ns, $MF=0.766$

Gate Delay = 25 ns, $MF=0.819$	Gate Delay = 25 ns, $MF=0.753$	Gate Delay = 25 ns, $MF=0.700$

Gate Delay = 19 ns, $MF=0.790$	Gate Delay = 20 ns, $MF=0.717$

Gate Delay = 13 ns, $MF=0.747$		
Figure 5.4 Images taken on various RITP regions for range gated ULIS (Refer to Table 5.1) The black spot on the images is due to accidental damage caused by a sharp laser beam.		

Table 5.1 and Figure 5.4 show the modified fidelity, MF index [10] and $OSBR$ for various images taken during an experiment conducted in different turbidity. MF has been compared with the recalculated $OSBR$ from MCRITP in Table 5.1. The water was mixed with Mylanta to achieve certain turbidity as shown in columns 3 and 4 of Table 5.1. The laser Q-switch was set to $190 \mu\text{s}$ (equivalent to 162 mJ/pulse) and the

time shown in columns 1, 2, and 5 of Table 5.1 are delayed timing when laser pulse exerted at the tank window. For all images taken, only the gate opening time was delayed for 4 – 6 ns at each stage, and all other parameters, such as camera focus, zooms, temperature etc, were kept constant during the experiment. In addition, it has been required to maintain the mean pixel value for each image taken to avoid the *MF* being seriously affected due to the high-energy pixel level [10].

The effective integration gate time (EIGT) was estimated to be 14 ns. For clear images, the *MF* value could be as high as 0.999 compared to the benchmark image taken in clear water conditions. For very bad images (See Figure 5.4), the *MF* is about 0.700. It means that the *MF* visual range is from 1.000 to 0.700. For a fixed target distance, the Actual RITP returned to the camera is delayed approximately from 25 to 37 ns from the detector signalling the lasing event (estimation from experiments in clear water condition). It should be noted that the recalculated *OSBR* is based on the centre-line (Figure 5.3) of target signal distribution in MCRITP simulation whereas the actual imaging responses range from 13 ns to 51 ns (37 ns + 14 ns) interval.

For $C = 1.38$ /m, the maximum *MF* is 0.840 (recalculated $OSBR = 1.2 \times 10^3$) for gate delay at 31 ns, whereas for gate delay at 37, the *MF* value is 0.811 (recalculated $OSBR = 8.3 \times 10^2$). Images with *MF* = 0.840 and 0.811 have been captured approximately close to the tail RITP region. On the other hand, both the *MF* and *OSBR* values were lower in the front RITP region, where *MF* = 0.819, 0.790 and 0.747 (recalculated $OSBR = 8.3 \times 10^2$, 2×10^2 and 48). In the absence of significant camera noise, the *MF* value has correlated well with recalculated *OSBR* from MCRITP. Similar results were observed in water conditions $C = 1.82$ /m and $C = 2.07$ /m.

By comparing front RITP images (about 25 ns delay in Figure 5.4) to the tail RITP images (about 37 ns delay in Figure 5.4) quantitatively, the latter are improved by about 4 % - 22 % (based on *MF* index) in various turbidity levels. Thus, it is observed that the range gated ULIS image quality would be improved by off synchronizing the gate opening time towards the tail RITP region. This is confirmed by the *MF* index, recalculated *OSBR* and also by subjective evaluation.

5.4.2 Shorter gate durations

In 1991, Strand [38] simulated the range-gated imaging system to depict the Modulation Transfer Function (*MTF*) at low spatial frequencies growing with increased gate duration. Hence, shorter camera gate duration is expected to generate better image quality for typical range-gated imaging system.

This section clarifies that shorter gate duration should be properly located within the right interval to achieve highest *OSBR*. Shorter gate duration may not necessary produce better *OSBR* if it is not gated at the correct interval. Equation 5.9 describes *OSBR* as a function of gate timing, backscattering noise variation and target signal distribution. This has enabled analytical predictions to determine the correct gate duration and gate opening time with a given operating condition.

From Figure 5.3, each double arrow line represents the *OSBR* for gate durations of 10 ns, 6 ns and 2 ns respectively. As an example, if the gate duration is chosen as 2 ns centred at 40 ns timing, the *OSBR* calculated is at least 100% better than for 10 ns gate duration.

5.4.3 Shorter pulse lengths

Before the formulation of backscattering noise variation with Equation 5.3, it was normally perceived that the backscattering noise is constant for various pulse lengths with constant amount of outgoing energy, $P_o(t)$ per pulse. Thus, the SBR improvement might be achievable due to higher target signal peak energy per pulse. However, this perception is not valid if the camera is considered as a light energy integration device with finite gate time, because the total amount of target signal integrated by the camera is still the same for both longer and shorter pulse lengths. Thus, the analysis of backscattering noise variation for various pulse lengths with constant outgoing energy per pulse is needed. Based on Equation 5.9, $P_o(t)$ integrated over t_2 to t_1 will produce the same results provided the total energy per pulse is the same. However, the fixed upper-limits effect has reduced the backscattering noise nonlinearly for shorter pulse length, t_0 as described in Equation 5.7.

Analytically, shorter outgoing pulse length will produce less backscattering noise within the Actual RITP, even with the same outgoing energy per pulse for both longer and shorter pulse length.

In the example illustrated in Figure 5.5, Equation 5.5 is used to generate various pulse functions ranging from $\sigma = 3$ ns to 0.6 ns. For fixed gate duration (6 ns) centred at the signal peak, the *OSBR* for $\sigma = 0.6$ ns is about 40% (6 ns fixed gate duration) and 400% (variable gate duration, 4σ ns) better than $\sigma = 3$ ns respectively. It should be noted that even if the pulse length is reduced and the signal peak is higher, the total target signal energy integrated by the camera (fixed at 6 ns gate duration or at variable gate duration, 4σ ns) is still about the same as for longer pulse lengths. The significant improvement of *OSBR* is because of the reduction of backscattering noise due to the fixed upper-limit convolution effect.

Figure 5.5 illustrates maximum *ISBR*(t) (located at tail RITP region) of each pulse length respectively. Maximum *ISBR*(t) can be improved by 100 times from $\sigma = 3$ ns to 0.6 ns, though the target signal energy per unit time is only about 5 times higher. This analysis has resulted in a correction of backscattering noise and SBR understanding. Nevertheless, this indicates possible improvement of range-gated image quality if a shorter pulse is used with an equivalent power of illumination.

5.5 Chapter summary

This chapter first studies the backscattering phenomenon within the target irradiance (Actual RITP) due to opaque target effect. It is described as a convolution with a fixed upper-limit based on Falk's LIDAR equation, when the opaque target effect has interfered with the target irradiance pulse. This phenomenon results in the variation of backscattering noise within the actual RITP (Equation 5.4). This variation is a function of pulse length, gate timing, TPSF, and outgoing power function due to the opaque target effect. It subsequently results (mainly as a function of pulse length and gate timing) in the variation of the SBR.

This chapter focuses only at gate timing, transmitted/outgoing pulse lengths, and gate duration issues. Both single and multiple backscattering noise models are computed for a near target range-gated imaging system. The diverged beam propagation in turbid medium is simulated in increased turbidity levels by using Monte Carlo simulation (MCRITP).

It has been explained analytically and verified experimentally that the tail RITP gating will produce higher SBR than front RITP gating. This corresponds with Witherspoon et al. [37] observations while McLean et al. [39] have opposite observations. The former observation is verified and proof to be correct in this thesis. However, none of them offers theoretical/physical insight into the backscattering issue. The formulations in this Chapter have analytically predicted the variation of $ISBR(t)$, which is higher towards the tail region of RITP. Thus, Witherspoon's observation is correlated with the derived equations, the Monte Carlo simulation, and the experimental results. Whereas, McLean's conclusion is applicable to a trans-illuminated gated imaging system in which the backscattering noise issue is basically non-existent. Therefore, the major contribution of this Chapter is to verify Witherspoon's observation with analytical, experimental, and simulated results.

It should be additionally remarked that if the delayed gate opening time were used for target range computation, it would subsequently introduce an error in target range detection. This error could be corrected based on quantitative RITP study.

It is a common belief that the range-gated images are expected to be better if shorter pulse length and gate duration are used. However, there is no analytical approach to predict or explain logically how the Signal to Backscattering Noise Ratio (SBR) could

be related to the overall performance of range gated image quality as a function of pulse length and gate time effect. By using Equation 5.9 and Monte Carlo simulation, this thesis predicts that shorter gate duration may not necessarily produce better *OSBR* if it is not gated at correct intervals, such as at the tail RITP. Based on Equation 5.7, shorter outgoing pulse length will produce less backscattering noise within the Actual RITP, even with the same energy per pulse for both longer and shorter pulses. Thus, this analytical approach provides correction to the backscattering understanding and explains why shorter pulses can generally produce better SBR than longer pulse length.

As the final remark, the signal scattered noise, $P_{SMM}(t)$ is considered negligible compared to the total backscattering noise in near target condition. Therefore, there is room for improvement if $P_{SMM}(t)$ is included into both the formulation and simulation for higher turbidity levels. This would contribute to the optimization of image quality with quantitative SBR study.

From the computational perspective, the MCRITP tends to show higher statistical error because the receiver size is too small for sufficient temporal data resolution of target response, $P_{target}(t)$. In order to compensate for this error, the receiver area and number of photons are increased until a smooth response of target signal, $P_S(t)$ is obtained after the convolution in Equation 5.6. The algorithm could be further enhanced to mimic the actual receiver size by deploying various variance reduction schemes in future. The RITP evaluations may include other factors, such as camera sensitivity, sensor noises, target distance, target reflectivity issues, etc. This will subsequently contribute to the optimization of range-gated imaging system performance.

At this stage, the RITP analysis is focused on simple single-target-single-pulse conditions. This analysis will not be completed without the consideration of multiple targets or extended three-dimensional target within the same FOV of multiple gated images. Thus, the following chapter proposes a novel image fusion framework for multi-target image sequences. This new framework will enable suppression of scattering noises and fusion of target feature based on specific characteristics of gated images.

In terms of practical development, the range-gated imaging system could be used to capture clear images not just in turbid water, but also in dynamic environment (moving targets, variations of target reflectivity, unstable system response due to temperature effects etc.). Thus, the camera parameters and target characteristics should also be considered to further enhance the output signal to noise ratio with the existing equipment specifications. Subsequently, an adaptive tail end range-gated technique is potentially possible to fine-tune the output image quality in harsh environments.

CHAPTER 6

IMAGE PROCESSING FOR RANGE-GATED IMAGES

This Chapter reports a preliminary analysis of the fusion framework for range-gated images. While RITP analysis in the previous chapter focuses on single-pulse-single-target conditions, multiple targets or extended target issues could be considered as multiple complex RITP arriving on every pixel of a gated image. For multi-target or extended target situations, the range-gated imaging system has to be sequentially gated in increased range to cover all targets within the FOV. This has motivated the research to fuse the images together to form a complete FOV with larger depth of view. In this preliminary analysis stage, a simple technique is found effective to fuse incremental or sequential range images together with some inherent drawback. This image fusion framework is a combination of both image enhancement and fusion schemes to integrate the enhanced portions of multiple targets or extended target images.

6.1 Introduction

The range-gated imaging system is proven to effectively enhance the underwater image quality in turbid conditions as disserted in Chapter 4 and 5. The study is focused only on single-target-single-pulse configuration. For multi-target or extended target conditions, the range-gated images have to be sequentially gated in increased range (in fixed time steps) to cover all targets within the FOV. These individual gated images (part of the target(s)) may not be fully comprehensive and presentable for human observations. In other words, the individually gated images have provided enhanced visibility but they do not separately carry much meaningful interpretation or the wider picture of the whole scene within the FOV. Thus, this has motivated the research to investigate the possibility to fuse the images together to form a complete scene with larger depth of view. This approach is similar to the working principle of the streak tube camera [20], but in 2 dimensional and multi-pulse configurations.

In this chapter, the gated images are sequentially acquired with multiple pulses at different gate opening times. In other words, it is gated at different ranges or slices of the target image. Figure 6.1 illustrates one of the experiments carried out for multi-

target fusion in the Robotics Research Centre. This setup is basically similar to the laboratory setup described in Chapter 4.

Individual targets are normally located at different positions in the FOV. Sequentially, the front image (nearer gate opening time) possesses close target features that are about 1.0 meter from the camera as shown in Figure 6.2a. The same position will be just a shadow or multiply scattered noise in the following gated images. Nevertheless, the residual backscattering noise is also stronger for the non-target region in the front image. This backscattering noise might cover the location of more distant target features, which will appear in the respective range image of subsequent gate timing (Figure 6.2b about 1.8 meter, and 6.2c about 2.4 meter). Figure 6.3 illustrates single-target-single-pulse RITP with two different target distances. This effect could be

taken as a complex response of separate pixels in multi-target conditions in time domain.

<p align="center">a</p> <p><u>Common Characteristics</u></p> <ul style="list-style-type: none"> - Possess higher backscattering noises (slow variation of image background intensities). - Stronger target intensities and signal to background ratio - Lower sensor noise due to lower gain applied 	<p align="center">b</p> <p><u>Common Characteristics</u></p> <ul style="list-style-type: none"> - Not concerned within the scope of this project. 	<p align="center">c</p> <p><u>Common Characteristics</u></p> <ul style="list-style-type: none"> - Possess lower backscattering noise. - Weaker target intensities and signal to background ratio - Higher sensor noise due to high gain applied - Shadows appear on the front target locations
<p>Figure 6.2 Sequentially gated images in extended target condition, from a) closest, b) middle, and c) furthest target location. The black spot on the images is due to accidental damage caused by a sharp laser beam.</p>		

Figure 6.2 lists some of the common characteristics of near and far target images respectively. For target sizes larger (coarser) than image resolution, these common characteristics seem to be image impairment, but it might become a helping factor in designing fusion algorithm for this application. Thus, an appropriate image fusion scheme should consider these issues specifically for multi-target gated images in future. This Chapter highlights the fundamental analysis that will lead to the theoretical derivation of a novel application of image fusion in gated noisy imaging condition.

Image fusion, or sensor fusion can be performed at three distinct levels, namely signal or pixel-level fusion, feature or object-level fusion and decision-level fusion [188]. In other lexicons, the fusion architectures could also be classified based on the extent of the data processing [189], such as sensor-level fusion, central-level fusion and hybrid fusion. The main objectives [188] are to transfer all visually important information from input images into a fused image and to minimize undesirable distortions and artefacts that should not appear in the fused image. This is normally achievable while working on multi-spectral [190], multi-sensor, multi-exposure and multi-focus [191]

fusion without much image impairment or inherent noises. For turbid imaging conditions, there are scattering noises in each individual gated image as well as the sensor noises. Thus, the fusion considerations for gated imaging are more difficult than those the traditional image fusion objectives.

In order to minimize network data transmission of remotely operated imaging system, low-level fusions such as pixel-level fusion schemes are generally applied without concentrating on particular points of interest [192]. There are numerous choices of image fusion schemes based on their mathematical approaches and assumptions made. Bretschneider et al. [193] identify various fusion algorithms, such as wavelet, transformation, addition and multiplication, filter, inter-band relation based etc. They concluded that there is no superior method that is suitable for all applications. Instead, the best technique has to be chosen on a case-by-case basis.

The most popular fusion method is based on a multi-scale approach [188]. There are also more advanced algorithms that have combined both feature-level and pixel-level fusion schemes together to enhance the fusion accuracy. Among them, Zhang et al.

[194], [195] have contributed substantially by using a region-based multi-scale decomposition method in concealed weapon detection applications.

For images affected by sensor noises, Petrovic [196] observed that the arithmetic (or averaging) fusion scheme is better than advanced schemes in low signal to noise ratio conditions. This sensor noise has also appeared on the range-gated images, especially in high intensified gain conditions. However, an arithmetic scheme may also reduce the image contrast as well as the noises. This observation is further verified in Petrovic's paper in 2003 [197]. Thus, the arithmetic scheme might not be desirable for range-gated imaging systems in highly turbid seawater condition.

As described in Chapter 1, images obtained from an underwater imaging system are frequently degraded due to absorption and scattering effects from their environment. The absorption effect reduces the signal strength, and the (forward scattered and backscattered) scattering effect reduces both signal strength and image resolution. Generally, the forward scattered target image, A_p (in spatial domain) could be modeled based on the Generic LIDAR Model [141] as:

$$MTF(\omega, R) = e^{-B_f R + B_f R \left[\frac{1 - e^{-2\pi\theta_0\omega}}{2\pi\theta_0\omega} \right]} \quad (6.1)$$

where θ_0 is the mean scattering angle, B_f is the forward component of the total scattering coefficient B . R is the propagation distance and ω is the angular frequency. The range of validity of the MTF is investigated in detail with the help of Monte Carlo runs from J. S. Jaffe [125]. From the signal's point of view, image A_p is equivalent to $P_s(t)$ in Chapter 4 and 5.

As for backscattering noises, the appearance of $P_{BSN}(t)$ is generally perceived as un-even illumination (or intensity value) of an image. One of the examples is clearly shown in Figure 6.2a and 6.2b. It should be noted that the un-even illumination of an image is also caused by the large-FOV-small-FOI system (spot system, system 1 [79]). This chapter focuses only on the backscattering noise of a diverged beam illumination system (system 2 and 3 [79]). Though the backscattering noise could be evenly distributed for the whole image due to small-FOV-large-FOI, the fundamental characteristics of backscattering noise in the image are still maintained. In this thesis, $P_{SMM}(t)$ is assumed to be negligible.

As a conclusion, a turbid medium not only attenuates the high spatial frequencies of image transmitted, but it also induces low spatial backscattering frequencies on the image itself.

Sensor noises are generally the result of several physical processes associated with the recording mechanism. They are normally considered as dark current and sampling noise [197] (illustrated in Figure 6.2c). These noises are basically considered as additive noises where the output image could be modeled as:

$$A_n = A_p + k_n N_s \quad (6.2)$$

A_p and A_n represent the non-sensor noise and with sensor noise image respectively. N_s represents the noise-seed signal, n is the signal to noise ratio in dB and k_n is the appropriate scaling factor. In this thesis, aliasing noise due to the saturation of CCD wells is ignored.

Prior to the fusion of range-gated images, the quality of each individual gated image should be maximized with two distinct stages, namely system upgrading and optimization (as presented in Chapter 1).

In the first stage, the imaging system could be upgraded with hardware or advanced imaging techniques based on the available resources and operational objectives, such as using higher illumination power, a better camera, or an advance imaging technique etc. This stage has been addressed in Chapter 4. Once the initial design framework is determined, the second stage will try to optimize the system signal to noise ratio and efficiency within the existing hardware solution, such as fine-tuning the gate timing (proposed in Chapter 5), gain control parameters, image processing etc. This concept is basically corresponding to the development of underwater imaging methods proposed by F. M. Caimi [198] in 1996.

This Chapter extends the work scope of the optimization stage by fusing the individual targets together. It is assumed that the residual backscattering and sensor noises should be minimal after the first optimization stage in Chapter 5. The residual noise should be erasable with most common image enhancement and fusion techniques available. This proposed second stage of the optimization stage - image fusion framework is a combination of three phases, namely enhancement, registration, and fusion itself.

In order to capture the complete depth of view image in multi-target conditions, it is proposed to fuse the images with the framework shown in Figure 6.4. This framework does not consider the exact target location within the FOV. It can be incorporated into future fusion framework for the non-target detected region of the images if target location is detectable (by accurate LIDAR scanning system, or by using incremental gating technique [199]).

First of all, the range-gated images are further enhanced with image processing techniques. These processed images will then be aligned geometrically (image registration and normalization) before the actual fusion take place. This approach is similar to the work done by Ramac et al. [200] and Sluzek et al. [201]. Ramac et al. used a morphological filter to eliminate undesired small objects of the source images before the wavelet fusion process while Sluzek et al. [201] applied modified contrast stretching before the image averaging took place.

The next sections report the use of four selected image enhancement techniques and their performance respectively (Section 6.2 & 6.3). Those image enhancement techniques chosen are reportedly suitable for turbid medium applications. They are Homomorphic Filtering [202], Illumination-Reflectance Model [202], Adaptive Histogram Equalization [202], [203], and Contrast Stretching [201].

In the development phase, the image quality indexes are assumed to be the quantitative measures of the enhancement scheme's performance in laboratory conditions. In order to determine the most suitable image enhancement and fusion technique for range-gated images, experimental evaluations in laboratory conditions

are required to establish the reference image in clear water conditions without significance distortion. For actual underwater deployment, the selected image enhancement technique should be able to reliably improve the image quality in a turbid medium.

Subsequently, the registration process should ensure the best match between two or more images for the image fusion process. For high gating frequency or slow underwater motion conditions, it is assumed that the image mis-matching problem is negligible. Thus, only the normalization of each gated image is performed to aid the fusion process in the following stage.

Once the individual images are co-aligned to each other, they can be fused together to form a complete two-dimensional clear image with standard video rate for human visual applications. This approach is similar to the work done by Mishra et al. [204] in 1995 for multi-spectral images.

In this chapter, only the first and third phases of this fusion process are reported. The main objective is to investigate the feasibility of incorporating the image enhancement and fusion scheme into range-gated imaging system applications.

6.2 Image Enhancement Schemes

This section suggests four image enhancement schemes from different processing domains. Each technique is claimed to eliminate certain image impairments of underwater imagery. The following sections will explain each individual image enhancement scheme separately.

6.2.1 Contrast stretching

Due to the limited illumination, the underwater images normally suffer from a narrow brightness range, often being represented in a histogram as a single peak close to the lowest intensity value. For illuminated underwater environments, Sluzek et al. [201] have used a specific contrast stretching in range-gated applications. Empirically, the upper and lower limits on the investigated image histogram are determined to stretch over the whole range of the new image histogram. They stretch the contrast specifically between the 1st and 98th percentile of the histogram only.

6.2.2 Contrast-Limited Adaptive Histogram Equalization (CLAHE)

The second scheme is Contrast Limited Adaptive Histogram Equalization (CLAHE), which has been used to deal with inherent non-uniform lighting in underwater imagery [202], [203], [205]. This technique subdivides the image into $n \times m$ blocks, calculating the histogram of each block. Every region is then equalized, by choosing a monotonically non-decreasing grey level transformation, mapped to the histogram of a desired distribution. For underwater images, the non-uniform nature of the light they receive could be enhanced to an optimal local histogram equalization scheme [205], [206], [207]. In this Chapter, the CLAHE variables, such as clip limits, window size etc, are based on default values used in Matlab[®]. In this case, the image is divided into 8×8 sections, and the clip limit is set to 0.01 with uniform distribution. It is suggested to fine-tune these variables for actual underwater applications in future developments.

6.2.3 Illumination-reflectance model

The third scheme is called the Illumination-Reflectance Model. It considers the image as a function of the product of the illumination and reflectance properties of a given scene. Garcia et al. [202] expressed the underwater image model as a reflectance function $f_I(i,j)$ adjusted by a multiplicative $c_m(i,j)$ and an additive $c_a(i,j)$ shading component:

$$f_I(i, j) = c_m(i, j) \times I_{cl}(i, j) + c_a(i, j) \quad (6.3)$$

where $I_{cl}(i,j)$ is the ideal image without shading.

From their derivation, the “equalized” version of an underwater image, $I(i,j)$ can be represented by:

$$I(i, j) = (I'(i, j) - \min(I'(i, j))) \frac{\tau_H - \tau_L}{\max(I'(i, j)) - \min(I'(i, j))} + \tau_L \quad (6.4)$$

where τ_H and τ_L are respectively the maximum and minimum desired values of $I(i,j)$; $\max(I'(i,j))$ represents the brightest grey level of image $I'(i,j)$ which is smaller than 1.5 times the third quartile of the histogram of $I'(i,j)$; and a similar approach is used for $\min(I'(i,j))$ with the first quartile.

6.2.4 Homomorphic filtering

Lastly, it is believed that backscattering noise could be high pass filtered by using Homomorphic Filtering [202]. This filtering technique assumes the illumination factor varies smoothly through the field of view, therefore generating low frequencies in the Fourier transform of the image. This approach takes into account only the multiplicative term $c_m(i,j)$ in Equation 6.3 while neglecting the additive $c_a(i,j)$ function. Transforming the spatial domain to Fourier domain, a typical transfer function for the homomorphic filter is approximated as,

$$H(\omega_x, \omega_y) = \frac{1}{1 + e^{-s_1(\sqrt{\omega_x^2 + \omega_y^2} - \omega_0)}} + \rho_1 \quad (6.5)$$

where ω_x , ω_y , and ω_0 are the horizontal, vertical and cut-off frequencies respectively, s_1 is a multiplicative factor and ρ_1 is an offset term. In this chapter, the homomorphic filter is applied with the shape as shown in Figure 6.5. The coefficients s_1 , ρ_1 and ω_0 are determined empirically for the best image quality tested. It is suggested to fine tune these coefficients used for actual underwater applications in the future.

6.3 Discussions on Image Enhancement Schemes

Table 6.1 and Figure 6.6 illustrates the original range-gated (same as Table 4.1) and enhanced range-gated images. From our computation results, the *MSR2* index is omitted here because of its narrow dynamic range from 0.99-0.97 for all turbidity

levels. It is difficult to measure the image quality if the *MSR2* index is not normalized to two extreme references. Thus, only the *MF* and *CNR* index will be used in this section.

Turbidity	Level 1	Level 2	Level 3
Gated Image
Contrast Stretching
CLAHE
Illumination – Reflectance Model
Homomorphic Filtering ($\omega_0 = 10, \rho = 0$)

Table 6.1. Enhanced range-gated images in increased turbidity. The black spot on the images is due to accidental damage caused by a sharp laser beam.

The calculated *MF* and *CNR* show higher image quality for Contrast Stretching, CLAHE, and Reflectance-Illumination Models. However, the homomorphic filtering technique does not improve the gated images in increased turbidity. This has also agreed well with subjective observations. Nevertheless, CLAHE, seems even better than the other three techniques generally, but this observation is not reflected in the quantitative indexes.

It should be noted that the image enhancement processes have also amplified the image noises, especially the residual backscattering noise. This situation is particularly obvious in Contrast Stretching, the Illumination-Reflectance Model (Level 3 in Table 6.1) and Homomorphic Filtering (All Levels). CLAHE, in particular, has substantially amplified the additive noise due to its localized windowing process. This effect may cause the MF index to be insensitive to overall visual enhancement from this imaging technique. Comparatively, CLAHE is more suitable to gated images in the subsequence fusion process, due to its enhancement effect in backscattering noise conditions. More results are presented in Appendix D to further verify this observation.

In conclusion, it is possible to further enhance the gated images with the Sluzek, CLAHE, and Illumination-Reflectance Models. However, the techniques produce comparably varied quality at this stage. Further investigation should be carried out to fine-tune each parameter of the enhancement scheme.

6.4 Image Fusion Schemes

This section address the problem of pixel level fusion or the so-called image fusion for gated images based on the framework proposed in Figure 6.4. A pre-requisite for successful image fusion is that multi-target images have to be correctly aligned on a pixel-by-pixel basis. It is assumed that the images are aligned due to the high repetitive rate of gating process that could “freeze” the relative target motions. After the enhancement process, only the normalization of each image by its own maximum intensity is taken for consideration at this stage of development.

As shown in previous section, CLAHE has successfully minimized the residual backscattering or uneven illumination of gated images. However, it has also magnified the localized additive noises. Thus, Petrovic’s [197] approach should be adopted to cater the image fusion with additive noise condition. From their conclusions, the arithmetic fusion scheme [196], [197] has best performance in low signal to noise ratio conditions. For T number of images fusion scheme, this averaging computation could be simply defined as

$$I_{fd}(i, j) = \sum_{t=1toT} k_t I_t(i, j) \quad (6.6)$$

where $I_{fd}(i, j)$ is the fused image, k_i equal to $1/T$. $I_t(i, j)$ are the individual images before the normalization process.

In this chapter, this scheme is compared to a simple image fusion scheme based on the framework proposed in Figure 6.4. After the normalization step, the images are fused based on “Choose-Max” (CM) method.

6.5 Quality Measure for Image Fusion

As presented in Section 2.1.4 and 4.4, quantitative scales are always needed to evaluate the performance of a given imaging system or technique. For image fusion analysis, there are various attempts to quantify the image quality of the final product compared to an ideal reference or individual images. The first quantitative measure to evaluate or compare image fusion schemes is proposed by Li et al. [207] in 1994. They need an ideally fused image that can be created by manual cut and paste of the individual image portions, $I_{pr}(i, j)$. The performance index ρ_2 is defined as

$$\rho_2 = \sqrt{\frac{\sum_{i=1}^N \sum_{j=1}^M [I_{pr}(i, j) - I_{fd}(i, j)]^2}{N \times M}} \quad (6.7)$$

where $I_{pr}(i, j)$ is the perfect result and $I_{fd}(i, j)$ is the fused image. For gated images in turbid medium, the performance of an image fusion scheme is also considered by its ability to suppress image noises while extracting target features from each individual image. Thus, the perfect reference could be assumed as the non-gated image captured in clear water conditions. However, this performance index does not detect the target features extracted by a given scheme while reflecting only the relative difference between noisy images to a clear water reference image.

Recently, G. Piella [209] proposed a statistical measure to evaluate the image fusion quality. Unfortunately, this measure is not suitable in this application because it is defined specifically for the fusion of two images only.

In 2000, Xydeas et al. [210] proposed another image fusion measure to evaluate several pixel-level fusion schemes. They associated important visual information with the ‘edges’ that are present in each pixel of an image. They use this index for two images fusion analysis. In this Chapter, a three-image fusion (compared to two-images fusion used in Petrovic’s works) is considered. Similarly, it could be applied up to T number of images.

A Sobel operator is applied to yield the edge strength $g_I(i, j)$ and orientation $\alpha_I(i, j)$ information for each pixel $I(i, j)$, $1 \leq i \leq N$ and $1 \leq j \leq M$. Thus, for an input image A_p , this quality index could be easily expanded as

$$g_1(i, j) = \sqrt{s_1^x(i, j)^2 + s_1^y(i, j)^2} \quad (6.8)$$

$$\alpha_1(i, j) = \tan^{-1}\left(\frac{s_1^y(i, j)}{s_1^x(i, j)}\right) \quad (6.9)$$

where $s_I^x(i, j)$ and $s_I^y(i, j)$ are the output of the horizontal and vertical Sobel templates centred on pixel $I_I(i, j)$ and convolved with the corresponding pixels of image A_p . The relative strength and orientation values of $G^{IF}(i, j)$ and $A^{IF}(i, j)$ of an input image A_p with respect to fused image F_{fused} are formed as

$$G^{1F}(i, j) = \begin{cases} g_F(i, j) / g_1(i, j) & \text{if } g_1(i, j) > g_F(i, j) \\ g_1(i, j) / g_F(i, j) & \text{otherwise} \end{cases} \quad (6.10)$$

$$A^{1F}(i, j) = 1 - \frac{|\alpha_1(i, j) - \alpha_F(i, j)|}{\pi / 2} \quad (6.11)$$

These are used to derive the edge strength and orientation preservation values

$$Q_g^{1F}(i, j) = \frac{\Gamma_g}{1 + e^{\kappa_g (G^{1F}(i, j) - \sigma_g)}} \quad (6.12)$$

$$Q_\alpha^{1F}(i, j) = \frac{\Gamma_\alpha}{1 + e^{\kappa_\alpha (A^{1F}(i, j) - \sigma_\alpha)}} \quad (6.13)$$

$Q_g^{1F}(i, j)$ and $Q_\alpha^{1F}(i, j)$ model the perceptual loss of information in F_{fused} , in terms of how well the strength and orientation values of a pixel $I(i, j)$ in A_p are represented in the fused image. The constants Γ_g , κ_g , σ_g and Γ_α , κ_α , σ_α are determined empirically[210] ($\Gamma_g=0.9994$, $\kappa_g=-15$, $\sigma_g=0.5$ and $\Gamma_\alpha=0.9879$, $\kappa_\alpha=-22$, $\sigma_\alpha=0.8$).

Subsequently, edge information preservation values are then defined as

$$Q^{1F}(i, j) = Q_g^{1F}(i, j) Q_\alpha^{1F}(i, j) \quad (6.14)$$

with $0 \leq Q^{1F}(i, j) \leq 1$. Similarly, the subsequent edge information preservation values $Q^{2F}(i, j)$ and $Q^{3F}(i, j)$ for other individual images could be calculated based on Equation 6.8-6.14. Having three individual images, a normalized weighted performance metric $Q_p^{1F}(i, j)$ of a given fusion process P_{fused} that operates on all three images, and produces F_{fused} is defined by Petrovic et al.. as

$$Q_p^{123/F} = \frac{\sum_{i=1}^N \sum_{j=1}^M [Q^{1F}(i, j)w_1(i, j) + Q^{2F}(i, j)w_2(i, j) + Q^{3F}(i, j)w_3(i, j)]}{\sum_{i=1}^N \sum_{j=1}^M [w_1(i, j) + w_2(i, j) + w_3(i, j)]} \quad (6.15)$$

At this stage, it is generally assumed the weighted coefficients are equal to $g_1(i, j)$, $g_2(i, j)$ and $g_3(i, j)$ respectively.

For fusion of noisy images, the quantitative measure should be related to the “loss” of input noise information, which is the desired characteristic of the underlying fusion process [196]. Thus, in order to correctly model the loss of noise information, it is solved with measuring only the representation of true scene information in the fused image. This information is contained in the clear water input images whereas the fused image F_{fused} is produced by noisy images in higher turbidity. Thus, $Q_p^{123/F}$ will be used to quantify the “fusion” quality of gated images in the following section.

6.6 Discussions on Image Fusion Schemes

From Section 6.3, CLAHE is used in the image enhancement phase of Figure 6.4. It is chosen because of its high performance in reducing backscattering noises in the images compared to other image enhancement methods. This Chapter aims to compare the arithmetic (averaging) fusion method and simple “Choose-Max” method in increased turbidity conditions. For both methods, enhanced images (by CLAHE) are used.

Table 6.2 compares both the averaging and “Choose-Max” fusion methods in increased turbidity. The averaging method is considered good for backscattering and additively noisy images, while “Choose-Max” is used to allow a preliminary study on this novel fusion application.

The $Q_p^{123/F}$ is calculated based on clear water individual images and the fused image in respective turbidity levels. From naked eyes observations, the “Choose-Max” method outperforms the averaging method for all turbidity levels. This has corresponded to a quantitative $Q_p^{123/F}$ index. The “Choose-Max” method shows 0.58, 0.3, and 0.20 compared to 0.32, 0.21, and 0.18 for the averaging method in increased turbidity.

It should be noted that the averaging method attenuates the additive noises as well as the target signal. This effect is increasing if more than three images are fused together. While for the “Choose-Max” method, the signal noise is basically weaker than the target intensity. This would allow the fusion method to choose the “right” target feature based on the pixel intensity itself. This effect may not produce better image quality if the noises are higher than the target intensity.

Turbidity level		Enhanced individual images (upper row) & Fused image (lower row)		
Clear Water
		Closest Target	Middle Target	Farthest Target

		Averaging ($Q_p^{123/F} = 0.32$)		Choose-Max ($Q_p^{123/F} = 0.58$)
Medium Turbidity Water
		Closest Target	Middle Target	Farthest Target

		Averaging ($Q_p^{123/F} = 0.21$)		Choose-Max ($Q_p^{123/F} = 0.30$)
High Turbidity Water
		Closest Target	Middle Target	Farthest Target

		Averaging ($Q_p^{123/F} = 0.18$)		Choose-Max ($Q_p^{123/F} = 0.20$)
Table 6.2 Comparison of arithmetic (averaging) and Choose-Max (after normalization) fusion methods. The black square on the images covers the accidental damage caused by a sharp laser beam.				

In order to clearly illustrate the effect of noise that could not be eliminated in the enhancement stage, another set of images is tested with the same fusion methods as shown in Table 6.2. These images (Table 6.3) are captured without the gate fine-tuning process proposed in Chapter 5. Thus, the gated images in Table 6.3 appear to possess higher backscattering noise compared to the images shown in Table 6.2.

Turbidity level	Averaging method	“Choose-Max” method
Clear water
	$Q_p^{123/F} = 0.54$	$Q_p^{123/F} = 0.60$
Level 1
	$Q_p^{123/F} = 0.30$	$Q_p^{123/F} = 0.35$
Level 2
	$Q_p^{123/F} = 0.26$	$Q_p^{123/F} = 0.26$
Level 3
	$Q_p^{123/F} = 0.22$	$Q_p^{123/F} = 0.22$
Level 4
	$Q_p^{123/F} = 0.18$	$Q_p^{123/F} = 0.19$
Table 6.3 Comparison of arithmetic (averaging) and Choose-Max (after normalization) fusion methods with strong noises after the enhancement stage.		

Table 6.3 lists both methods of fusing three individual images (not shown in the table) in increased turbidity. The $Q_p^{123/F}$ are generally higher for the “Choose-max” method. It produces fused images with 0.60, 0.35, 0.26, 0.22, and 0.19 compared to the averaging method that produces images with $Q_p^{123/F}$ ranging from 0.54, 0.30, 0.26, 0.22, and 0.18 respectively. However, naked eyes observations disagree with these quantitative results. From Table 6.3, we observe better image quality for averaging method than “Choose-Max” method. It might be because the “Choose-Max” and $Q_p^{123/F}$ have taken the strong backscattering noise as target features, while the averaging has basically attenuated this effect. With stronger target edges appearing on the “Choose-Max” fused images, the $Q_p^{123/F}$ indexes are generally higher but the noise has also degraded the overall perceptual quality of the images.

6.7 Chapter Summary

The main objective of this chapter is to investigate the feasibility of incorporating the image enhancement and fusion scheme into range-gated imaging system applications. A novel fusion framework is proposed, only the first and third phase of this framework are demonstrated and reported.

First of all, this Chapter investigates four possible image enhancement schemes to further improve the gated images in increased turbidity. These are the Contrast Stretching method described by Sluzek et al., CLAHE from Eustice et al., the Illumination-Reflectance Model, and Homomorphic Filtering from Rafael et al. Among them, the three former schemes improve the image quality, but only with limited levels of noise (up to level 2 turbidity). This is especially true for Contrast Stretching and the Illumination-Reflectance Model. Homomorphic filtering does not improve the image quality as well as predicted.

In conclusion, it is possible to further enhance the gated images with Contrast Stretching, CLAHE, and Illumination-Reflectance Model. However, the techniques produce comparably varied quality at this stage. There is potential to improve the algorithms if each variable of the respective schemes could be fine-tuned for actual underwater conditions in future. Besides, it is also desirable to have an advanced enhancement scheme that could eliminate the additive sensor noises as well as the scattering noises of gated images.

Among various image enhancement processes, CLAHE seems effective in improving the underwater image quality by reducing the scattering noise effects. However, this effect is not largely reflected in the image quality scales. In this Chapter, it is chosen as the enhancement scheme in eliminating the residual backscattering noise from the gated images.

At this stage, the use of an image enhancement scheme to eliminate the residual backscattering noise of gated images is demonstrated.

An arithmetic fusion technique is found effective to fuse noisy images together. However, the technique attenuates the additive noise and the target signal. This effect is worsening if more images are fused together. Table 6.2 compares both the averaging and “Choose-Max” fusion methods in increased turbidity. The averaging method is considered good for additive noisy image, while the “Choose-Max” method is used to allow preliminary study on this novel fusion application.

If the signal noise is generally weaker than the target intensity, the “Choose-Max” method will be able to choose the “right” target features based on the pixel intensity itself. This effect may not produce better image quality if the noises are higher than the target intensity. Thus, a more advance image fusion technique is desirable to extract the target feature correctly in images with a very high level of noise (very high turbidity). This will involve both modelling the image’s noise as well as the target signal. At this stage, it is considered as another PhD work scope for future research.

CHAPTER 7

CONCLUSIONS

This thesis presents some fundamental research issues of backscattering noise within the RITP of a range-gated imaging system in turbid seawater conditions. This includes a mathematical description of backscattering noise with an opaque target effect, numerical modelling and measurement of RITP, verification of the tail-RITP gating technique, an analytical approach to predict shorter pulse length and gate duration effect on improving gated image quality and fusion of multi-target or extended target images. In this chapter, the main contributions are summarized first, and the future research directions are outlined.

7.1 Contributions

The overall project work scope covers the development of an advanced underwater imaging system via two sequential stages, namely: hardware upgrading and system optimization stage. Specifically, it aims to improve the output image quality by using tail gating optimization and image processing techniques.

This section highlights the academic contributions of this project as below:

7.1.1 Propose a novel formulation to investigate the backscattering noise within RITP

A newly defined term is introduced as Reflected Image Temporal Profile (RITP). It describes the timely characteristics of target irradiance and backscattering noise superimposed with each other at the receiver aperture.

This thesis studies the backscattering phenomenon within the target irradiance (Actual RITP) due to the opaque target effect. It is described as a convolution with a fixed upper-limit based on Falk's LIDAR equation, when the opaque target effect has interfered with the target irradiance. This phenomenon results in the variation of backscattering noise within the actual RITP (Equation 5.4). This variation is a function of pulse length, gate timing, TPSF (Temporal Point Spread Function), and outgoing power/source function, due to the opaque target effect. It was subsequently related (mainly as a function of pulse length and gate timing) to the variation of SBR (Signal to Backscattering noise Ratio).

In order to analyze the variation of SBR within the RITP, the diverged beam propagation for a near target range-gated imaging system is simulated in increased turbidity levels by using the Monte Carlo simulation (MCRITP). It is further verified in the time domain analytically and empirically.

This is also the first experimental demonstration of Yaroslavsky's model accounting for a scattering delay time larger than the mean time of flight between interactions, such as highly forward scattering phenomenon in seawater conditions.

7.1.2 Verify tail-gating concept analytically

The formulations (Chapter 5) have analytically predicted the variation of $ISBR(t)$ (Instantaneous Signal to Backscattering noise Ratio), which is higher towards the tail region of the RITP. From the analysis, the tail RITP gating will produce a higher SBR than front RITP gating. Subsequently, Witherspoon's observation is correlated to the equations derived (Chapter 5), the Monte Carlo simulation and the experimental results.

This technique can optimize the range-gated image quality for short target distance in turbid water conditions.

7.1.3 Theoretical examination of gate time and pulse length effects for better image quality from the perspective of SBR

It is common to believe that the range-gated images are expected to be better if shorter pulse lengths and gate durations are used. However, there is no analytical approach to predict or explain correctly how the SBR could be related to the overall performance of range-gated image quality as a function of pulse length and gated time effect.

By using Equation 5.9 and Monte Carlo simulation, this thesis predicts that shorter gate duration may not necessarily produce a better $OSBR$ (Overall Signal to Backscattering noise Ratio) if it is not gated at the correct intervals, such as off-gating towards the tail RITP region.

Based on Equation 5.7, a shorter outgoing pulse length will produce less backscattering noise within the Actual RITP, even with the same energy per pulse for both longer and shorter pulses. Thus, this analytical approach makes a correction of

backscattering noise within the actual RITP and explains why shorter pulses can generally produce a better SBR than longer pulse lengths.

7.1.4 Evaluates the performance of this system globally and quantitatively by correlating the output image quality in laboratory condition.

An advanced imaging system or image enhancement algorithm (used in a turbid environment) should produce as minimum scattering effect as the reference image in a clear water condition. The better the performance of a given system/algorithm, the image fidelity in the turbid condition will be closer to its reference image in clear water laboratory conditions. Therefore, it is proposed to evaluate the underwater image quality more objectively and globally based on this conclusion. This involves using quantitative indexes and a testing procedure in control environment.

The indexes calculate among the same set of images with constant geometrical and background effects. By keeping the target fixed in a camera field of view along the experiment, temporal and spatial distortions are minimized. Background noise and camera noises should be kept constant for all images taken for comparison. Image manipulation process should be kept to a minimum. The only desired changes in this image quality evaluation are the turbidity of the seawater and the camera control parameters, such as gated and non-gated configurations, while other hardware parameters are maintained.

From this procedure, at least 40% (calculated based on the MF values) improvement is achieved for the current range-gated imaging system (compared to non-gated imaging system) in high turbidity levels (5.3 AL). Nevertheless, there is another 4-22% of improvement in the experiments for the tail-gating concept compared to the front RITP gated images.

7.1.5 Proposes a novel framework for gated image fusion in multi-target or extended target condition

The RITP analysis is focused on simple single-target-single-pulse conditions. This analysis will not be completed without the consideration of multi-target or extended three-dimensional target within the same FOV of multiple gated images. Thus, this thesis proposes a novel image fusion framework for multi-target images for human visual applications. The proposed image fusion framework is a combination of three

phases, namely enhancement, registration and fusion itself, applied to incremental gated images in increased ranges.

In this thesis, only the first and third phases of this fusion process are reported. The contribution of this work is to assess the feasibility of incorporating the image enhancement and fusion scheme into range-gated imaging system applications.

The use of an image enhancement scheme to eliminate the residual backscattering noise of gated images is demonstrated. For image fusion, the averaging method is considered good for backscattering and additive noisy images, while the “Choose-Max” method is adequate for negligible backscattering noise affected images.

7.2 Future Directions

In terms of practical development, the range-gated imaging system could be used to capture clear images not just in turbid water, but also in dynamic environments (moving targets, variations of target reflectivity, unstable system response due to temperature effects etc). Thus, the RITP evaluations may include other factors, such as camera sensitivity (or Effective Integration Gate Time, EIGT), sensor noises, (multi-) target distances, (multi-) target reflectivity issues, etc. This has subsequently motivated the future works listed below:

7.2.1 System engineering

One of the challenges presented in this project is the non-linear characteristic of effective camera gate duration in ns speed (Explained in Section 4.2.4). The input gate duration from the DG535 might be longer than the actual camera gate duration (in Gaussian profile). The analysis of EIGT should be investigated as a function of outgoing power function, turbidity level, target reflectivity, gain applied etc. This analysis is needed for actual or quantitative tail gating optimization applications.

It should be additionally remarked that if the delayed gate opening time were used for target range computation, it would subsequently introduce an error in target range detection. Thus, the quantitative estimation of the optimal position of range gating will be useful to correct this error and to optimize the image quality.

7.2.2 Performance evaluation

In order to fine-tune the image quality in an optimization process, two quantitative approaches (visibility and image quality) are suggested to serve as the performance

index feedback to the imaging control system or to reflect the capability of a given imaging system. There are the “underwater visibility” index and the quantitative image quality index. The latter is preferred for the near target range-gated imaging system application in this thesis. However, the indexes used in this thesis are applicable in laboratory conditions only. It needs a reference image that is normally impossible for actual underwater applications. In this case, a performance index based on the real time system without the reference is needed in future.

In extremely turbid conditions (or high attenuation length), the “underwater visibility” is one of the performance indexes that had not been used extensively in underwater imagery evaluations. This index is perceived as an alternative of image quality indexes, which is suitable in evaluating underwater optical detection systems if clear image quality is not available or required.

7.2.3 The Monte Carlo Method (MCM)

For current MCRITP simulations, the simulated geometry is a semi-infinite model without a target laid in front of the laser and camera. The reflections or absorptions from sidewalls are considered negligible compared to the total backscattering noise from the medium. Hence, there is room for improvement for MCRITP, the reflection from the sidewalls should be included in future work to further enhance the simulation results in this laboratory condition.

It should be noted that $P_{SMM}(t)$ would be higher than $P_{BSN}(t)$ for higher attenuation lengths and wider FOV conditions when the multi path time is significant. $P_{SMM}(t)$ should be considered in higher attenuation lengths and wider FOV conditions in future works.

For light propagation in turbid media, it is quite difficult to obtain precise descriptions of the features and performance of specific MCM codes without going into detail through the publications respectively. Thus, it was suggested to standardize the general framework and verifications procedure of the MCM, to enable the selections and comparisons of various MCM implementations. Unfortunately, despite various categorizations to describe MCM implementations, there is no effort leading to this direction so far.

From the computational perspective, the MCRITP tends to show higher statistical error because the receiver size is too small for sufficient temporal data resolution of

the target response, $P_{target}(t)$. In order to compensate for this error, the receiver area and number of photons are increased until a smooth response of target signal, $P_S(t)$ is obtained after the convolution in Equation 5.6. The algorithm could be further enhanced to mimic the actual receiver size by deploying various variance reduction schemes in the future.

7.2.4 Multi-target or extended target analysis

In conclusion, it is possible to further enhance the gated images with the Sluzek, CLAHE, and Illumination-Reflectance Model. However, the techniques produce comparable quality at this stage. It is also desirable to have an advanced/fine-tuned enhancement scheme that could eliminate the additive sensor noises as well as the scattering noises of the gated images.

If the signal noise is basically weaker than the target's intensity, the "Choose-Max" will be able to choose the "right" target feature based on the pixel intensity itself. This effect may not produce better image quality if the noises are higher than the target intensity. Thus, a more advanced image fusion technique is desirable to extract the target feature correctly even in noisy images. This will involve both modelling the image noises as well as the target signals. At this stage, it is considered as another PhD project for future research.

Specifically, the common characteristics of near and far target images are studied respectively. These common characteristics seem to be image impairment, but it might become a helping factor for target range detection (multiple RITP study) and image fusion in this application.

7.3 Concluding remarks

At the time of writing this thesis, we observe that "smart pixel" technology is introduced. This new technology has built-in computation circuit to capture the target range, with much higher time resolution and sensitivity compared to a typical Gen2 MCP gated camera. By using this new technology, the sensor model for conventional gated camera will be different and may not be valid anymore. However, the backscattering noise analysis (not limited to typical sensor noise analysis) presented in this thesis will be crucial as it is not just explaining the right understanding of SBR within the RITP, but also allow the target range correction to be embedded into the pixel level computation.

From the contribution section, we highlighted the possible of image fusion for multi-target images. This process is believed to be easier and simplified by the new technology because the continuous time response of a medium can be computed accurately at pixel level. From the future work section, we highlighted the possible improvement in the gated system, the evaluation method, the MCM and the multi-target fusion methods. All these works are hoped to contribute to the new technology as well.

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6. **ChingSeong Tan**, Gerald Seet, Andrzej Sluzek, DuoMin He "A Novel Application of Range-Gated Underwater Laser Imaging System (ULIS) in Near Target Turbid Medium," Elsevier, Optics and Laser in Engineering, Vol. 43 Issue 9, September 2005, page 995-1009.
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APPENDIX A

MATHEMATICAL DEFINITION FOR OCEAN OPTICS

For the direction indicated by the solid angle vector radiance ξ , the radiant flux dF per solid angle $d\Omega$ per elementary area dA with the ξ_0 normal is

$$I(\vec{x}, \xi) = dF / \cos \psi dA d\Omega \quad (\text{A1})$$

where $\cos \psi = (\xi \xi_0)$ is the cosine of the angle between the solid angle vectors ξ and ξ_0 . The quantity $I(\vec{x}; \xi)$ [$\text{Wm}^{-3}\text{sr}^{-1}\text{nm}^{-1}$], a radiant flux per unit solid angle per unit area normal to ξ , is referred as the radiance.s

Consider some volume element dV in a scattering and absorbing medium, which is illuminated over a solid angle $d\Omega$ by an incident light beam with radiance I . This volume will partly absorb and partly scatter the incident flux. The absorbed flux turns out to be

$$dF_a = a I d\Omega dV \quad (\text{A2})$$

where a is the absorption coefficient.

The intensity dI of the light scattered by a volume element in the direction making an angle ψ , to the incident beam is assumed to be

$$dI = V S F(\theta) I(\vec{x}, \xi) d\Omega dV \quad (\text{A3})$$

$V S F(\psi)$ is the volume scattering function in ψ angle.

Naturally, the radiant flux scattered in all directions is

$$dF_s = \int_{4\pi} dI d\Omega' = I d\Omega dV \int_{4\pi} V S F(\theta) d\Omega' = B \cdot I d\Omega dV \quad (\text{A4})$$

where B is the scattering coefficient of a volume element. It is convenient to describe the relative angular distribution of the radiant intensity scattered by a volume element by the function

$$\beta(\psi) = 4\pi V S F(\psi) / B \quad (\text{A5})$$

normalized by the relation

$$\frac{1}{4\pi} \int_{4\pi} \beta(\psi) d\Omega = 1 \quad (\text{A6})$$

This characteristic is called the scattering indicatrix, or phase function. For isotropic scattering,

$$\beta(\psi) = 1 \quad (\text{A7})$$

However, the real scattering indicatrix is generally far from isotropic. They may be rather complex functions of the scattering angle. Figure A1 shows some of the example for seawater phase function, which normalized to 90° directions. These examples (500 nm in wavelength) are compared to the analytical approximation used in this thesis, Henyey-Greenstein phase function (HG).

APPENDIX B

MECHANICS OF PHOTON PROPAGATION

This section outlines the detailed Monte Carlo algorithm used in Chapter 3. It begins by launching a photon into the medium from the source point based on the FOI definition. A photon is uniquely described by six variables: three spatial coordinates for the position, two directional angles for the direction of travel and photon weight (equal to one initially).

Figure B1. MCRITP (Similar to Figure 3.2)

Once launched, the photon is moved a distance dl based on Equation 3.5 where it may be scattered, absorbed, propagated undisturbed, internally reflected, or transmitted out of the medium. At the end of each traveled distance, the photon weight is deducted by its previous weight multiplied by $(1-\Lambda)$. For a photon weight larger than a predefined

threshold (such as 0.01), the photon is repeatedly moved until it either escapes from or is absorbed by the medium.

For scattering events, this thesis treated the photon's spatial position with Cartesian coordinates and the direction of travel with three direction cosines. The required formulae for propagation are simpler, and the angle variables describing photon direction do not change unless the photon's direction changes. The direction cosines are specified by taking the cosine that the propagation angle makes with each axis. These are specified by μ_x , μ_y and μ_z corresponding to each of the x -, y -, and z -axes respectively (Figure B2a). For a photon located at (x, y, z) traveling a distance dl in the direction (μ_x, μ_y, μ_z) , the new coordinates (x', y', z') are given by

$$\begin{aligned} x' &= x + \mu_x dl \\ y' &= y + \mu_y dl \\ z' &= z + \mu_z dl \end{aligned} \tag{B1}$$

If a photon is scattered at an angle (ψ, ϕ) from the direction (μ_x, μ_y, μ_z) in which it is traveling (Figure B2b), then the new direction of propagation (μ'_x, μ'_y, μ'_z) is specified by

$$\begin{aligned} \mu'_x &= \frac{\sin \psi}{\sqrt{1 - \mu_z^2}} (\mu_x \mu_z \cos \phi - \mu_y \sin \phi) + \mu_x \cos \psi \\ \mu'_y &= \frac{\sin \psi}{\sqrt{1 - \mu_z^2}} (\mu_y \mu_z \cos \phi - \mu_x \sin \phi) + \mu_y \cos \psi \\ \mu'_z &= -\sin \psi \cos \phi \sqrt{1 - \mu_z^2} + \mu_z \cos \psi \end{aligned} \tag{B2}$$

If the angle is too close to the normal ($\mu_z > 0.999999$), the following formulae should be used

$$\begin{aligned} \mu'_x &= \sin \psi \cos \phi \\ \mu'_y &= \sin \psi \sin \phi \\ \mu'_z &= \cos \psi / \mu_z \end{aligned} \tag{B3}$$

to obtain the new photon directions.

The new scattering angle could be determined based on its probability density function or phase function. Any phase function may be used with the Monte Carlo method. A normalized phase function describes the probability density function for the angle at which a photon is scattered. In this thesis, the Henyey-Greenstein phase function is used to characterize the random scattering angles with non-uniform distributions. It is defined as

$$p(\cos \psi) = \frac{1}{2} \frac{1 - g_{HG}^2}{(1 + g_{HG}^2 - 2g_{HG} \cos \psi)^{3/2}} \quad (B4)$$

The random number K represents the cumulative probability distribution function for this phase function as

$$K = \int_0^\psi p(\cos \psi') d \cos \psi' \quad (B5)$$

Thus, the generating function for this distribution obtained using Equation B5 is

$$\cos \psi = \frac{1}{2g_{HG}} \left\{ 1 + g_{HG}^2 - \left[\frac{1 - g_{HG}^2}{1 - g_{HG} + 2g_{HG}K} \right] \right\} \quad (B6)$$

For a photon weight smaller than the predefined threshold, the photon is either absorbed or scattered based on the roulette technique. It states that the probability that a photon is scattered is equal to the single scattering albedo. If K is a random number uniformly distributed between zero and one, then the photon is scattered if

$$K < \Lambda \quad (B7)$$

Otherwise, the photon is absorbed. If a photon is scattered, then a new photon direction is chosen based on the phase function, otherwise the photon is absorbed and a new photon is launched.

APPENDIX C

THE EQUIPMENT SETTINGS

General Equipment Setting/Controls

Continuum Surelite Laser		reference	Surelite manual
Item	Description	Controls	Experiment Setting
AC Power	Power on and Check LEDs&Software	On/Off	On
Key	Total # discharges, Start Flo, last freq.	On/Standby	On
Select	6 modes: Freq., Q-switch, Pulse/discharge, PumpVlt,Serial Mode, ExternalMode	Varies	F20, 100us, P01, Sof, Eof, 1.18kV
RS232 port	Connected to computer	Page 3-16	Not connected
Ext port	Connected to TTL circuit	Page 3-21	Not Connected
EXT QSWH select	select EXT control or internal control	INT(mode 1)/EXT(mode 2)	INT
Single shot in	Single shot firing	Page 4-11	Not connected
Variable Synh out	Varied signal output from 325 before & 450ns after lasing	Page 4-11, adjustable	Not connected
Fixed Synh Out	Fixed signal output about 100ns before lasing	Page 4-11	Not connected
Flashlamp Synh Out	Signal output about 180us before lasing output.	Page 4-11	Connected to DG535

ISG-250 Xybian camera		reference	ISG-250 manual
Item	Description	Controls	Experiment Setting
AGC	Automatic gain control	on/off	Off
Peak/Average	Image peak/average level control	enable/disable w.tuner	Enable
Level	Control sensitivity	CW/Anti CW	As appropriate
Frame/Field	60/30 frame persec.	Frame or Field	Frame
Range control	see page.5 ISG manual	1 – 8	Autogating
Delay	Delay in shooting	0 – 100	0
Connetions	External control/synh/Asynh.	Page 37 - 41	Connected
Gate readout	Low TTL pulse read out (2.4 - 0.8 VDC)	Page 42	Connected to TDS oscilloscope
Video out	RS-170 video output		Connected to Video if needed
Lens	Lens control		Not connected

General Equipment Setting/Controls (Continued)

CCU-01 Camera Control Unit		reference	CCU-01 manual
Item	Description	Controls	Experiment setting
Trigger source	Trigger the camera signal source	VD, HD, EXT, Bypass	Bypass
Intensifier	Intensifier gain control	min to max	as appropriate
Control	Auto-adjustment of exposure time	Auto/Manual	Auto
Camera Gain	Image peak/average level control	tuning	N/A (Not applicable)
Black level	Control sensitivity	tuning	N/A
Range	Camera gate range preset range	Pos. 1/others.	N/A
Duration	Range tuning	Fast tune/Slow tune	N/A
Delay	Delay of camera trigger upon triggering	tuning	0
Aux port	Page 17		Not connected
Video out	RS-170 video output		Connected to Video & PC
Gate readout	CCU camera gate signal		N/A
Camera connection	Page 13 - 16		Connected
Genlock	Synchronize of camera-camera signal.	Genlock & H&V	
Mode	Frame(25CCIR/30RS170) Field(50CCIR/60RS170)	Frame/Field	Frame
Auto trigger	Retrigger camera to VD if EXT signal missing	Enable/Disable	Enable
VD IN	Frame(25CCIR/30RS170) Field(50CCIR/60RS170)		Not connected
VD OUT	Frame(25CCIR/30RS170) Field(50CCIR/60RS170)		N/A
HD IN	63.5us for RS170, 64 us for CCIR		Not connected
HD OUT	63.5us for RS170, 64 us for CCIR		Not connected
Image Inhibit	Multiple shot over same image		Not connected
Pixel Clock			Not connected
External trigger	Input for external trigger		Connected to DG535
Gain readout	Output from camera gain		Not connected

APPENDIX D

MORE RESULTS ON IMAGE ENHANCEMENT SCHEMES

Turbidity level	Level 1	Level 2	Level 3
Original Image
	The Reference Image		
Contrast Stretching
	$MF = 0.998; CNR = 8.148$	$MF=0.962; CNR=4.429$	$MF=0.952; CNR=4.225$
CLAHE
	$MF=0.964; CNR=4.697$	$MF=0.926; CNR=3.541$	$MF=0.905; CNR=2.924$
Illumination – Reflectance Model
	$MF=0.997; CNR=56.748$	$MF=0.949; CNR=4.056$	$MF=0.958; CNR=3.680$
Homo-morphic filtering ($\omega_0 = 10, \rho = 0$)
	$MF=0.881; CNR=2.432$	$MF=0.882; CNR=2.460$	$MF=0.885; CNR=2.52$

Turbidity level	Level 1	Level 2	Level 3
Original Image
	The Reference Image		
Contrast Stretching
	$MF = 1.000$; $CNR=11.159$	$MF=0.927$; $CNR=3.278$	$MF=0.912$; $CNR=2.765$
CLAHE
	$MF=0.953$; $CNR=4.579$	$MF=0.891$; $CNR=2.740$	$MF=0.889$; $CNR=2.324$
Illumination – Reflectance Model
	$MF=0.999$; $CNR=81.108$	$MF=0.932$; $CNR=2.655$	$MF=0.919$; $CNR=2.197$
Homo-morphic filtering ($\omega_0 = 10$,
	$MF=0.897$; $CNR=2.656$	$MF=0.871$; $CNR=2.096$	$MF=0.893$; $CNR=2.360$
Table D1. MF and CNR results on images produced by various image enhancement schemes as described in Section 6.2. Noted that CLAHE amplified least backscattering noise, but inevitably magnify the additive sensor noises.			