

# IMPROVED TIME-FREQUENCY DE-NOISING OF ACOUSTIC SIGNALS FOR UNDERWATER DETECTION SYSTEM

YASIN YOUSIF MOHAMMED

A thesis submitted in fulfilment of the  
requirements for the award of the degree of  
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering  
Universiti Teknologi Malaysia

MAY 2017

To my beloved family, friends and  
all those who have contributed in this project

## ACKNOWLEDGEMENT

First and foremost, I would like to express my sincere appreciation to my supervisor, Assoc. Prof. Dr. Ahmad Zuri Bin Sha'ameri for his continuous guidance, suggestions, comments, and encouragement in the journey of making this research project a success. Without his thoughtful views and ideas, this thesis would not have been as what was presented here. My honest appreciation goes to my Co-Supervisor Assoc. Prof. Dr. Nor Hisham Haji Khamis for his prudent scientific instruction and revision.

In addition, my gratitude goes to the Ministry of Higher Education (MOHE) Malaysia for its financial support and Universiti Teknologi Malaysia for providing the resources for this research. Other than that, I would also like to thank the entire DSP Laboratory team members who have contributed through ideas, feedbacks, and supports. Moreover, I would like to thank the Ministry of Higher Education and Scientific Research, Iraq for providing Doctoral scholarship for my study.

I want to thank all my friends who have distinguished themselves by giving me strength, encouragement and guidance. Other than that, I would like to thank the Wonderful Dr. Saad Shukri for his continuous support and his medical advice throughout my studies.

I am deeply thankful to my family for their love, support, and sacrifices. Without them, this thesis would never have been written. This last word of acknowledgment I have saved for my lovely wife Jenan Al-Aboosi, who has been with me all these years and has made them the best years of my life.

## ABSTRACT

The capability to communicate and perform target localization efficiently in underwater environment is important in many applications. Sound waves are more suitable for underwater communication and target localization because attenuation in water is high for electromagnetic waves. Sound waves are subjected to underwater acoustic noise (UWAN), which is either man-made or natural. Optimum signal detection in UWAN can be achieved with the knowledge of noise statistics. The assumption of Additive White Gaussian noise (AWGN) allows the use of linear correlation (LC) detector. However, the non-Gaussian nature of UWAN results in the poor performance of such detector. This research presents an empirical model of the characteristics of UWAN in shallow waters. Data was measured in Tanjung Balau, Johor, Malaysia on 5 November 2013 and the analysis results showed that the UWAN has a non-Gaussian distribution with characteristics similar to  $1/f$  noise. A complete detection system based on the noise models consisting of a broadband hydrophone, time-frequency distribution, de-noising method, and detection is proposed. In this research, S-transform and wavelet transform were used to generate the time-frequency representation before soft thresholding with modified universal threshold estimation was applied. A Gaussian noise injection detector (GNID) was used to overcome the problem of non-Gaussianity of the UWAN, and its performance was compared with other nonlinear detectors, such as locally optimal (LO) detector, sign correlation (SC) detector, and more conventionally matched filter (MF) detector. This system was evaluated on two types of signals, namely fixed-frequency and linear frequency modulated signals. For de-noising purposes, the S-transform outperformed the wavelet transform in terms of signal-to-noise ratio and root-mean-square error at 4 dB and 3 dB, respectively. The performance of the detectors was evaluated based on the energy-to-noise ratio (ENR) to achieve detection probability of 90% and a false alarm probability of 0.01. Thus, the ENR of the GNID using S-transform denoising, LO detector, SC detector, and MF detector were 8.89 dB, 10.66 dB, 12.7dB, and 12.5 dB, respectively, for the time-varying signal. Among the four detectors, the proposed GNID achieved the best performance, whereas the LC detector showed the weakest performance in the presence of UWAN.

## ABSTRAK

Keupayaan untuk berkomunikasi dan melaksanakan sasaran penyetempatan yang cekap bawah air adalah penting dalam banyak aplikasi. Gelombang bunyi adalah lebih sesuai untuk komunikasi dan sasaran penyempatan dalam air kerana pengecilan dalam air adalah tinggi untuk gelombang elektromagnet. Gelombang bunyi adalah tertakluk kepada bunyi akustik bawah air (UWAN), sama ada buatan manusia atau semula jadi. Pengesanan isyarat optimum dalam UWAN boleh dicapai dengan mengetahui tentang statistik hingar. Andaian hingar Gaussian putih tambahan (AWGN) membolehkan penggunaan pengesanan korelasi linear (LC). Walau bagaimanapun, sifat bukan-Gaussian untuk UWAN menyebabkan prestasi yang tidak baik terhadap pengesanan tersebut. Kajian ini menjelaskan tentang model empirikal bagi ciri-ciri UWAN di perairan cetek. Data diukur di Tanjung Balau, Johor, Malaysia pada 5 November 2013 dan keputusan analisis menunjukkan bahawa UWAN mempunyai pembahagian bukan-Gaussian dengan ciri-ciri yang serupa dengan hingar  $1/f$ . Satu sistem pengesanan lengkap berdasarkan model hingar yang terdiri daripada hidrofon jalur lebar, taburan masa-frekuensi, kaedah nyah-hingar dan pengesanan adalah dicadangkan. Dalam kajian ini pengubahan-S dan pengubahan gelombang digunakan untuk menghasilkan perwakilan masa-frekuensi sebelum pengambungan lembut dengan penganggaran ambang universal terubah digunakan. Pengesanan hingar Gaussian (GNID) telah digunakan untuk mengatasi masalah *non-Gaussianity* daripada UWAN, dan prestasinya telah dibandingkan dengan pengesanan linear lain, seperti pengesanan optimum setempat (LO), pengesanan tanda korelasi (SC) dan beberapa lagi pengesanan penapis sepadan konvensional (MF). Sistem ini telah dinilai berdasarkan dua jenis isyarat iaitu isyarat termodulasi frekuensi-tetap dan frekuensi linear modular. Untuk tujuan nyah-hingar, pengubahan-S mengatasi pengubahan wavelet dari segi nisbah isyarat-kepada-hingar dan ralat punca min kuasa dua masing-masing pada 4 dB dan 3 dB. Prestasi pengesanan dinilai berdasarkan nisbah tenaga-kepada-hingar (ENR) bagi pengesanan kebarangkalian sebanyak 90% dan kebarangkalian penggeraan palsu sebanyak 0.01. Oleh itu, ENR daripada GNID menggunakan nyah-hingar pengubahan-S, pengesanan LO, pengesanan SC, dan pengesanan MF adalah masing-masing 8.89 dB, 10.66 dB, 12.7 dB dan 12.5 dB, untuk isyarat yang berubah dengan masa. Antara empat pengesanan, GNID yang dicadangkan mencapai prestasi terbaik manakala pengesanan LC menunjukkan prestasi yang paling lemah dengan kehadiran UWAN.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xi
	LIST OF FIGURES	xii
	LIST OF ABBREVIATIONS	xvii
	LIST OF SYMBOLS	xix
	LIST OF APPENDICES	xxiii
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Background of Research	1
	1.2 Problem Statement	3
	1.3 Objectives	4
	1.4 Scope of Work	5
	1.5 Research Procedure	6
	1.6 Contributions of Work	7
	1.7 Thesis Organization	8
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>10</b>
	2.1 Introduction	10

2.2	Basics of Underwater Communications	10
2.3	Sound Velocity in the Ocean	12
2.4	Propagation Effects	13
2.5	Channel Model	18
2.5.1	Ray Model	20
2.5.2	Rays Distance Calculation	22
2.5.3	Reflection at the Sea Surface	23
2.5.4	Reflection at the Sea Bottom	23
2.5.5	Propagation Delay	24
2.6	UWAN Characteristics	25
2.6.1	Noise Sources - Ambient Noise	25
2.6.2	Noise Sources - Self-Noise	28
2.6.3	Noise Sources - Intermittent Sources of Noise	29
2.6.4	Variability of UWAN	30
2.7	Signal Detection Methods in Gaussian and Non-Gaussian Noise	30
2.7.1	A Brief Review of Bayesian Detection Theory	31
2.7.2	Detection of Signal in Noise	35
2.7.3	Neyman-Pearson Criterion	36
	2.7.3.1 Null Hypothesis	37
	2.7.3.2 Alternate Hypothesis	37
2.7.4	Signal Detection Problem	38
2.7.5	Signal Detection in t-distribution Noise	40
	2.7.5.1 Matched Filter (MF)	41
	2.7.5.2 Locally Optimal Detector (LO)	43
	2.7.5.3 Sign Correlation Detector (SC)	46
2.8	UWAN Models	47
2.9	De-noising Methods	49
2.9.1	Filtering Method	50
2.9.2	Wavelet Method	51
2.9.3	Pre-whitening Method	54
2.9.4	S-transform Method	55

2.10	Signal Detection	58
2.10.1	Signal Detection in Colored Noise	59
2.10.2	Signal Detection in Non-Gaussian Noise	61
2.11	Summary	64
<b>3</b>	<b>SIGNAL DE-NOISING IN COLORED NOISE</b>	<b>65</b>
3.1	Introduction	65
3.2	Signal Model	66
3.3	De-noising of Signal in UWAN	69
3.3.1	De-noising Process Flow	69
3.3.2	Whitening Process and Inverse Whitening Filter	70
3.3.3	Signal Transformation	72
3.3.3.1	Wavelet Transform	73
3.3.3.2	S-Transform	80
3.4	De-noising Process	82
3.4.1	Wavelet Based Method	83
3.4.2	Selection of Modified Universal Threshold Factor ( $\xi$ )	86
3.4.3	S-transform Based Method	87
3.5	Performance Measures	93
3.6	Computation Complexity (CC)	94
3.7	Signal Detection with Gaussian Noise Injection (GNID)	96
3.8	Summary	103
<b>4</b>	<b>RESULTS</b>	<b>104</b>
4.1	Introduction	104
4.2	UWAN Characteristics	104
4.2.1	Statistical Properties and Estimation	105
4.2.2	Experimental Results	108
4.2.2.1	Sea Trial 1	108
4.2.2.2	Sea Trial 2	113
4.3	Signal De-nosing	119



4.3.1	Simulation Results	119
4.3.2	Experimental Validation	129
4.4	Signal Detection	132
4.4.1	Performance of the Detector	132
4.4.1.1	Performance of GNID Detector Using S-Transform Compared to other Detectors	133
4.4.1.2	Performance of GNID Detector Using Wavelet Transform Compared to other Detectors	137
4.4.2	Receiver Operating Characteristic (ROC) of the Detectors	141
4.4.2.1	ROC of the GNID Detector using S-transform	141
4.4.2.2	ROC of the GNID Detector using wavelet transform	145
4.5	Summary	149
<b>5</b>	<b>CONCLUSION AND RECOMMENDATION</b>	150
5.1	Conclusion	150
5.2	Recommendations and Future Work	152
	<b>REFERENCES</b>	154
	Appendix A-D	167-172

## LIST OF TABLES

TABLE NO	TITLE	PAGE
2.1	Available bandwidth for different ranges in underwater acoustic channels	10
2.2	UWAN band	26
3.1	Comparison of the maximum values at zero for different basis at input SNR given a 6 dB	74
3.2	Results of de-noised signal SNR for modified universal threshold estimation method at input SNR given a 6 dB	86
3.3	Comparison of computational complexity between S-transform and DWT	95
4.1	Parameter specification	109
4.2	Degree of Freedom for Different Depth	112
4.3	The output SNR and RMSE of the various de-noising methods and the input SNR given a 3 dB and input 1/RMSE given a 15dB	128
4.4	ENRs for various detection methods given a $P_D$ of 90 percent	136
4.5	ENRs for various detection methods given a $P_D$ of 90 percent	140

## LIST OF FIGURES

FIGURE NO	TITLE	PAGE
2.1	Typical deep water sound speed profile (SSP)	12
2.2	Underwater acoustic environment	13
2.3	Diagram indicating empirical formulae for different frequency domains	15
2.4	Transmission loss as a function of frequency	16
2.5	Transmission loss as a function of range	17
2.6	Channel-induced ISI	18
2.7	The Pekeris waveguide model of the shallow water acoustic channel	21
2.8	Average deep-water ambient noise spectral density levels	25
2.9	Power spectral density of the ambient noise over the frequency range from 1 Hz to 1000 kHz	27
2.10	Detection regions: Gaussian probability density functions	35
2.11	Schematic of the different detectors for known signal in non-Gaussian noise	40
2.12	Schematic of the matched filter (linear correlator)	41
2.13	Schematic of the LO detector for known signal in non-Gaussian noise	42
2.14	Nonlinear transfer function for a locally optimal detector in t-distribution noise with $d = 3$	42

3.1	De-noising methods	69
3.2	Block diagram for the PEF	70
3.3	Some of basis functions used in wavelet transform are: (a) Haar, (b) Symlet 6 (c) Debauchies 6 (d) Biorthogonal 1.5	73
3.4	Cross correlation of original signal and signal de-noise	74
3.5	Time-Frequency plane for STFT and CWT	76
3.6	Multiresolution analysis (MRA) using DWT	77
3.7	Signal reconstruction using wavelets	78
3.8	Each different f-value generates a different width of Gaussian curve, and hence a different width of kernel function and different resolution	80
3.9	Flow graph of the de-noising step (a) De-noising algorithm using pre-whitening filter. (b) De-noising algorithm without using pre-whitening	82
3.10	Hard and soft thresholding functions	84
3.11	Signal de-noising by thresholding of wavelet detail coefficients for $L=3$	85
3.12	Block diagram of the proposed de-noising method	91
3.13	Complete detection system design using whitening filter	96
3.14	Complete detection system design direct method	97
3.15	Region in xy plane where $x + y \leq Z$	99
3.16	Central part of p.d.f. of $Z = X + Y$ (solid line); Gaussian density for $X$ (dashed line); sphered Student's t distribution on 3 degrees of freedom for $Y$ (dotted line)	100
4.1	Test site for experiment	108
4.2	Field trials conducted at Tanjung Balau, Johor, Malaysia on the 5 November 2013	108
4.3	The equipment used Dolphin EAR 100 Series	109

4.4	Time representation waveform and autocorrelation function of the underwater acoustic noise for two different depths 5 meters and 9 meters	110
4.5	Welch Noise PSD estimate for two different depths	110
4.6	Welch Noise PSD estimate at 9 meters depths in logarithm scale	111
4.7	Comparison of the amplitude distribution of the UWAN with the Gaussian distribution and t-distribution	111
4.8	Analysis period 1.2 sec at depth 3 meters	112
4.9	Time representation waveform and autocorrelation function of the underwater acoustic noise for day and night at different depth	114
4.10	Welch Noise PSD estimate for day and night at five different depths	115
4.11	Welch Noise PSD estimate of UWAN for the day and night at depth 3 meters in logarithm scale	116
4.12	Comparison of the amplitude distribution of the UWAN with the Gaussian distribution and t-distribution for day and night at different depths	117
4.13	Output frequency bands of wavelet decomposition	119
4.14	Time representation of: (a): original signal; (b): noisy signal with SNR=6dB; (c): de-noisy signal using S-transform method; (d): de-noisy signal using wavelet method	121
4.15	Wavelet approximate coefficient ( $XA(n, 5)$ ) detail coefficients ( $XD(n, 1)$ - $XD(n, 5)$ ) of noisy signal at sampling frequency 8000 Hz	122
4.16	Time-frequency representation of noisy signal and de-noised signal using S-transform direct method [SNR of the signal is 6 dB]	124
4.17	Time-frequency representation for noisy signal and de-noised signal using S-transform method with pre-whitening filter [SNR of the signal is 6 dB]	125

4.18	Comparison of the output SNR obtained by using DWT methods and proposed S-transform de-noising methods	126
4.19	Comparison of the RMSE obtained by using DWT and proposed S-transform de-noising methods	127
4.20	Comparison of the output SNR experimental and simulation results obtained by using the S-transform direct method	129
4.21	Comparison of the RMSE experiment and simulation results obtained by using the S-transform direct method	130
4.22	Performances of the LO, SC, GNID, and LC detectors for the single-tone signal with 400 Hz frequency (S-transform)	133
4.23	Performances of the LO, SC, GNID, and LC detectors for the single-tone signal with 1500 Hz frequency (S-transform)	134
4.24	Performance of the LO, SC, GNID, and LC detectors for the LFM signal (S-transform)	135
4.25	Performances of the LO, SC, GNID, and LC detectors for the single-tone signal with 400 Hz frequency (wavelet transform)	137
4.26	Performances of the LO, SC, GNID, and LC detectors for the single-tone signal with 1500 Hz frequency (wavelet transform)	138
4.27	Performance of the LO, SC, GNID, and LC detectors for the LFM signal (wavelet transform)	139
4.28	ROC curves of the LO, SC, GNID, and LC detectors for the single-tone signal with 400 Hz frequency (S-transform)	141
4.29	ROC curves of the LO, SC, GNID, and LC detectors for the single-tone signal with 1500 Hz frequency (S-transform)	142

4.30	ROC curves of the LO, SC, GNID, and LC detectors for the LFM signal (S-transform)	143
4.31	ROC curves of the LO, SC, GNID, and LC detectors for the single-tone signal with 400 Hz frequency (wavelet transform)	145
4.32	ROC curves of the LO, SC, GNID, and LC detectors for the single-tone signal with 1500 Hz frequency (wavelet transform)	146
4.33	ROC curves of the LO, SC, GNID, and LC detectors for the LFM signal (wavelet transform)	147

## LIST OF ABBREVIATIONS

AWGGN	-	Additive White Generalized Gaussian Noise
AWGN	-	Additive white Gaussian noise
CC	-	Computation complexity
CWT	-	Continuous wavelet transform
DCT	-	Discrete cosine transform
DFT	-	Discrete Fourier transform
DWT	-	Discrete wavelet transform
ECL	-	Energy congregation level
EMD	-	Empirical mode decomposition
EEMD	-	Ensemble empirical mode decomposition
ENR	-	Energy-to noise ratio
FFT	-	Fast Fourier transform
FIR	-	Finite impulse response
GG	-	Generalized Gaussian
GNID	-	Gaussian noise injection detector
GPR	-	Ground penetrating radar
HIS	-	Hyperspectral image
IIR	-	Infinite impulse response
ISI	-	Intersymbol interference
IWT	-	Inverse wavelet transform
LC	-	Linear correlator
LFM	-	Linear frequency modulated
LMS	-	Least mean square
LO	-	Locally optimal
MF	-	Matched filter



ML	-	Maximum likelihood
MSE	-	Mean square error
NP	-	Neyman-Pearson
NRMSE	-	Normalized root-mean-square error
PD	-	Probability of detection
PEF	-	Prediction error filter
PPT	-	Parts per thousand
PRD	-	Percent root mean square difference
PSD	-	Power spectral density
PSE	-	Power spectral estimation
PWMWF	-	Whitening Multiway Wiener Filter
RMSE	-	Root mean square error
ROC	-	Receiver Operating Characteristic
SC	-	Sign correlation
SNR	-	Signal to noise ratio
SSP	-	Sound speed profile
STFT	-	Short-time Fourier transform
SVD	-	Singular value decomposition
SWPT-SURE	-	Spatial-domain wavelet packet transform with Sure
TD	-	Threshold-system-based detector
UHF	-	Ultrahigh frequency
WSS	-	Wide sense stationary
WT	-	Wavelet transform

## LIST OF SYMBOLS

$c$	-	sound speed in sea water
$T$	-	temperature
$d$	-	depth
$S$	-	Salinity
$PL_{spreading}$	-	Geometric spreading loss
$S_f$	-	Spreading factor
$R$	-	Transmission range
$PL_{absorption}$	-	Absorption loss
$f$	-	Signal frequency
$P$	-	Hydrostatic pressure
$f_T$	-	Relaxation frequency
$\alpha(f)$	-	Absorption coefficient
$PL$	-	Total path loss
$L_A(R)$	-	Natural value total path losses
$T_s$	-	Symbol duration
$T_m$	-	Time delay spread
$D_{00}$	-	Distance along direct ray
$D_{sb}$	-	Distance covered by the first ray reflected on the surface
$D_{bs}$	-	Distance covered by the first ray reflected on the seabed
$L_A(D_{00})$	-	Path losses along direct path
$L_A(D_{sb})$	-	Path losses covered by the first ray reflected on the surface
$L_A(D_{bs})$	-	Path losses covered by the first ray reflected on the seabed
$L_{SR}$	-	Surface reflection coefficients

$L_{BR}$	-	Sea bottom reflection coefficients
$\tau_{sb}$	-	propagation delay along the ray length $D_{sb}$
$\tau_{bs}$	-	propagation delay along the ray length $D_{bs}$
$h(\tau, t)$	-	channel impulse response
$A_p(t)$	-	time-varying path amplitude
$\tau_p(t)$	-	time-varying path delay
$d_1$	-	depth of the source
$d_2$	-	depth of the receiver
$h$	-	height of the water column
$v_m$	-	wind speed
$\theta$	-	incident angle
$\sigma$	-	<i>rms</i> roughness of the surface
$\lambda_a$	-	acoustic wave length
$\rho$	-	density in sea water
$\rho_1$	-	density in the seabed
$c_1$	-	sound speed in the seabed
$\theta_{sb}$	-	angle of incident corresponding to the ray $D_{sb}$
$\theta_{bs}$	-	angle of incident corresponding to the ray $D_{bs}$
$N_t(f)$	-	Turbulence noise
$N_s(f)$	-	Shipping noise
$N_w(f)$	-	Wind noise
$N_{th}(f)$	-	thermal noise
$s$	-	shipping density parameter
$S_{xx}(f)$	-	overall noise spectrum level
$s(n)$	-	Discrete time signal
$N$	-	signal duration in samples
$A$	-	signal amplitude
$\phi(n)$	-	instantaneous phase
$T_s$	-	sampling period
$\alpha$	-	frequency law
$f_{BW}$	-	bandwidth of the signal
$R_{vv}(m)$	-	Autocorrelation function
$s_{vv}[e^{j2\pi f}]$	-	power spectrum

$\sigma_v^2$	-	Variance of noise
$\sigma_v$	-	standard deviation of noise
$p$	-	length of the forward predictor filter
$a_p(n)$	-	filter coefficient
$e_p(n)$	-	forward prediction error
$H_p(z)$	-	transfer function of the PEF
$h_w(n)$	-	impulse response of the whitening filter
$h_{IWF}(n)$	-	impulse response of the inverse whitening filter
$X(t, a)$	-	continuous wavelet transform
$a$	-	Scale factor
$X(n, k)$	-	discrete wavelet transform
$L$	-	Number of levels
$\Delta f$	-	frequency resolution
$\Delta \tau$	-	Time resolution
$X_D(n, k)$	-	detail coefficients at scale $k$
$X_A(n, k)$	-	approximate coefficients at scale $k$
$h_{HP,k}(n)$	-	high-pass filter at scale $k$
$h_{LP,k}(n)$	-	low-pass filter at scale $k$
$X(t, f)$	-	S-transform
$g(t, f)$	-	frequency depended Gaussian window
$X(n, k)$	-	Discrete time of S-transform
$\gamma_k$	-	modified universal threshold estimation
$\xi$	-	modified universal threshold factor
$\sigma_{v,k}$	-	$k$ -th noise standard deviation
$X_{D,\gamma}(n, k)$	-	threshold values of the detail coefficients
$v_I$	-	in-phase component
$v_Q$	-	quadrature component
$W(k)$	-	scalable localizing Gaussian window
$CC_{ST}$	-	Computation complexity of S-transform
$N_\tau$	-	lag window length
$N_h$	-	length of the low-pass and high-pass filters
$CC_{DWT}$	-	Computation complexity of wavelet transform

$P_D$	-	detection probability
$C_{ij}$	-	cost
$l(x)$	-	likelihood ratio
$H_0$	-	null hypothesis
$H_1$	-	alternate hypothesis
$P_{FA}$	-	probability of false alarm
$P(D_i H_i)$	-	conditional probability
$P_M$	-	probability of missing
$d$	-	degree of freedom
$\mu_v$	-	mean value
$T(x)$	-	test statistic
$E_s$	-	energy of the signal
$g(x[n])$	-	non-linear transfer function of LO detector
$\Psi(\cdot)$	-	Kummer's hypergeometric function.
$\Gamma(\cdot)$	-	gamma function
$r_{xx}(t)$	-	autocorrelation function
$P_{welch}(e^{jw})$	-	Welch method

**LIST OF APPENDICES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Publication List	165
B	Time Representation Analysis of Underwater Acoustic Signals	167
C	Periodgram Representation of Underwater Acoustic Signals	169
D	Spectrogram Representation of Underwater Acoustic Signals	171

## Chapter 1

### INTRODUCTION

#### 1.1 Background of Research

Increased interest in defense applications, off-shore oil industry, and other commercial operations provides a motivation for research in signal processing for the underwater environment. In the underwater environment, acoustics waves are more practical for applications such as navigation, communication, and other wireless applications due to the high attenuation rate of electromagnetic waves. Acoustic propagation is characterized by three major factors: attenuation that increases with signal frequency, time-varying multipath propagation, and low speed of sound (1500 m/s) (Stojanovic and Preisig, 2009). No two deployment regions within the ocean have the same depths ranging from tens of meters to a few kilometers with node placement that varies from one network to another (King *et al.*, 2008). As the attenuation of sound in the ocean is a frequency-dependent process, underwater systems operate at low frequencies, for example, on the order of tens of kHz (Stojanovic and Preisig, 2009). Underwater data communication links generally support low data rates mainly due to the constraints of the communication channel (Burrowes and Khan, 2011; Stojanovic and Preisig, 2009). The main constraints are the high propagation delay, lower effective signal-to-noise ratio (SNR) and lower bandwidth. Sources of underwater acoustic noise (UWAN) are manmade (shipping,

aircraft over the sea and machinery sounds on the ship) and natural (rain, wind, marine lifeforms and seismic) (Melodia *et al.*, 2013).

As the attenuation of sound in the ocean is frequency dependent, the ocean acts as a low-pass filter for ambient noise. Results ambient noise power spectral density (PSD) is thus described as colored that is the noise has more power at the lower frequencies and less power at the higher frequencies (Chitre *et al.*, 2004). The ambient noise comes from sources such as turbulence, breaking waves, rain, and distant shipping. While ambient noise is often approximated as Gaussian, in practice it is colored exhibiting a decaying power spectral density (PSD). The rate of decay is at approximately 18 dB/decade (Burrowes and Khan, 2011). The underwater environment consists also site-specific noise (Burrowes and Khan, 2011). Site-specific noise, for example, exists for ice cracking in the polar region and acoustic noise due snapping shrimp in warmer waters. Unlike ambient noise, site-specific noise often contains significant non- Gaussian components.

In many signal processing applications, it is assumed that the noise samples are uncorrelated and typically described as independently identically distributed (i.i.d). Therefore, it is often necessary to transform a vector of observations with correlated noise samples to one in which they are uncorrelated (Therrien, 1992). This thesis is concerned with the de-noising and detection of signals that are generally transmitted by vessels sailing on the surface of the sea that could be due to the acoustic emission of the ship's engine or machinery and echo locating devices. The goal is to investigate on the techniques for optimal detection of acoustic signals in UWAN. To better understand the underwater operating environment, a comprehensive study was conducted with measurements of UWAN at Tanjung Balau, Johor, Malaysia.

In this thesis, a complete detection system based on the noise models is developed that consists of the broadband hydrophone, pre-whitening filter, time-frequency distribution, de-noising method, inverse whitening filter, and detection. It



is proposed to improve the probability of detection ( $P_D$ ) and increased the energy to noise ratio (ENR) using S-transform based time–frequency de-noising algorithm. The S-transform is used in the de-noising process to improve performance over de-noising using wavelet transform (Al-Aboosi *et al.*, 2016). The performance results using simulated and measured UWAN of the proposed detector Gaussian noise injection detector (GNID) are compared with other nonlinear detectors, namely, a locally optimal (LO) detector, a sign correlation (SC) detector, and a conventional LC detector.

## 1.2 Problem Statement

UWAN affects signal detection and parameters estimation. This is true in the reliability of signal detection where the noise is non-white and non-Gaussian. The sound attenuation in the sea is frequency dependent and this causes the sea acts as a low-pass filter for UWAN. The resulting PSD of UWAN is best described as colored where the noise has more power at the lower frequencies compared to the higher frequencies. Therefore, the noise samples are uncorrelated and the assumption of i.i.d is no longer valid resulting in poor detection performance.

The UWAN is often approximated as colored where the observed signal samples follows Gaussian probability density function (pdf). In practice, the signal observed on certain sites has significant non-Gaussian components. For example, ice cracking in the polar region and snapping shrimp in warmer waters. As a result, the detection methods that assume Gaussian pdf do not achieve optimum performance in UWAN. The effect of non-Gaussian pdf and colored noise further degrades the performance of the detection system such as underwater data communication and target locating. Further detector improvement performance can be achieved by combining non-linear detectors and de-noising process with pre-whitening techniques.

Signal de-noising is important if it is of interest to recover information in a signal that is corrupted by noise. For noise that is modeled as additive white Gaussian noise (AWGN), the frequency components of noise are evenly distributed over all frequency range while the signal of interest lies within a specific range in frequency. De-noising using time-frequency based method can be used to recover the signal from noise. Universal threshold estimation method is used widely to calculate the threshold value. Most critical is to find the suitable threshold value to ensure that the signal is recovered from noise. If the threshold value is too high, part of the original signal could be removed while a value too low could result in the insertion of noise in the signal.

### **1.3 Objectives**

1. To characterize UWAN for shallow water in Malaysian seas based on statistical properties such as power spectral estimation (PSE), autocorrelation function and probability density function (PDF).
2. To de-noise the acoustic signal in UWAN using the time-frequency representation generated by the S-transform with soft thresholding using the modified universal threshold estimation. The comparison is made with the conventionally used wavelet transform de-noising method.
3. To adopt methodologies used to de-noise a known signal in presence of colored noise that include pre-whitening filter, signal transformation and single-level and level-dependent thresholding method.
4. To design detection methods using linear and non-linear detectors for optimal or near-optimal performance in UWAN.

## 1.4 Scope of Work

This research focuses mainly on the de-noising and detection of acoustic signals using time-frequency representation. The scopes of this project are as follows:

1. The measurements were done in shallow water at Tanjung Balau, Johor, Malaysia with a maximum sea depth of 10 meters. The first set of measurements was done at different depths while another set was done to observe the diurnal difference in UWAN characteristics.
2. Samples of UWAN collected using a broadband hydrophone (7 Hz ~ 22 kHz) DolphinEAR 100 Series model with a maximum cable length 10 meters.
3. The Nyquist rate is used to convert the measured signal in continuous time to discrete time. Since the underwater acoustic signals is in the 0-2500 Hz frequency band, the sampling frequency is  $f_s=2W$  which the minimum requirement for digital sonar system. By making the sampling frequency greater than  $2W$ , the sampling frequency selected is 8000 Hz.
4. Different modulation signals are generated in MATLAB can be transmitted underwater using BII-8030 underwater acoustic transmitter for frequency range (20Hz to 100 kHz).
5. The UWAN can be assumed stationary because the variability of the predominant sources (wind speed and shipping density) and propagation variation (such as temperature and density) changes more slowly compare to the signal duration of interest.

6. Comparing the distributions obtained from the collected data with Gaussian distribution done by using distribution fitting tool in MATLAB to knowledge the pdf of the UWAN.
7. The signals used are divided into two types, namely, single-frequency sinusoidal signal and linear frequency modulated (LFM) signal, which respectively represent fixed-frequency signals and time-varying signals normally encountered in practical situations.

## 1.5 Research Procedure

The research procedure is as follows:

1. **Literature review:** Reviews on underwater communications, underwater acoustic noise models, time-frequency representation, signal de-noising, and signal detection.
2. **Data Collection:** Collect samples of noise from different depth in Malaysian seas using Hydrophone Dolphin EAR 100 Series (two field trials).
3. **Data Analysis:** Analyze noise samples and characterized them using Welch power spectrum estimation technique, the autocorrelation function of noise and probability density function (PDF). Also, to investigate the diurnal variability of UWAN characteristics.
4. **Pre-whitening filter:** Since the UWAN is colored noise, pre-whitening of the signal performs before the de-noising operation is implemented using the same methods use for white noise.

5. **De-noising technique:** The S-transform and the wavelet transform are used to generate the time-frequency representation before soft thresholding with universal threshold estimation is applied to de-noise the acoustic signals.
6. **Detection Theory:** Detection of the acoustic signal in the presence of UWAN, Gaussian noise injection detector (GNID) is proposed to overcome the problem of non-Gaussianity of the UWAN, and its performance compared with matched filter (MF) detector and other non-linear detectors. The performance of the detectors is evaluated based on the energy-to-noise ratio (ENR) and receiver operating characteristic (ROC) curves.
7. **Simulation validation:** To validate the performance of the complete detection system proposed. The complete detection system based on the noise models consist of the broadband hydrophone, pre-whitening filter, time-frequency distribution, de-noising method, inverse whitening filter, and detection.
8. **Discussion and result.**

## 1.6 Contributions of Work

1. In this work, a signal de-noising and detection system for acoustic signals corrupted by underwater acoustic noise (UWAN) is proposed. The proposed system overcomes the limitation caused by the characteristics of UWAN in shallow waters, which is identified as a key performance hurdle for communication systems.
2. The proposed Gaussian noise injection detector (GNID) detector based on noise-enhanced signal detection using an S-transform de-noising

method aims to ensure that the noise follows a Gaussian distribution, improve the detection probability ( $P_D$ ), and increase the energy-to-noise ratio (ENR) in comparison with other nonlinear detectors exclusively used for non-Gaussian detection. Thus far, this method has not been presented in previous research for sonar and underwater communication applications.

3. The S-transform de-noising method based on time–frequency analysis is proposed as an alternative to the wavelet transform. From the time–frequency representation generated by the S-transform, de-noising is performed using soft thresholding with modified universal threshold estimation. The threshold value for a single level estimation method is determined in the case of using a pre-whitening filter or the multilevel estimation method. Afterward, soft thresholding is applied to suppress the noisy coefficients and reconstruct the signal using the inverse S-transform. Thus far, no work based on S-transform de-noising used this methodology, and most of the previous works assumed that the noise is white and applied a mask window to the time–frequency domain representation of noisy signal to remove noises.

## 1.7 Thesis Organization

This thesis is organized as follows: Chapter 2 discusses a brief review of related topics, such as the sound speed profile, underwater propagation effects, underwater transmission loss, underwater channel model, non-Gaussian signal detection methods, UWAN characteristics and model, signal whitening and de-noising, and signal detection. Chapter 3 provides the details of the proposed signal de-noising technique using S-transform and the proposed detection systems in

presence of UWAN. Chapter 4 presents the experimental and simulation results. Chapter 5 presents the conclusion and recommendations for future research.

## REFERENCES

- Abramowitz, M. and Stegun, I. A. (1972). *Handbook of mathematical functions: with formulas, graphs, and mathematical tables*. Courier Dover Publications.
- Aggarwal, R., Singh, J. K., Gupta, V. K., Rathore, S., Tiwari, M. and Khare, A. (2011). Noise reduction of speech signal using wavelet transform with modified universal threshold. *International Journal of Computer Applications*. 20(5), 14-19.
- Ahsanullah, M., Kibria, B. G. and Shakil, M. (2014). *Normal and Student's T Distributions and Their Applications*. Springer.
- Akram, J., Chen, Z., Eaton, D. and Wei, X. (2016). Time-frequency denoising of microseismic data *SEG Technical Program Expanded Abstracts 2016* (pp. 2750-2754) Society of Exploration Geophysicists.
- Akyildiz, I. F., Melodia, T. and Chowdhury, K. R. (2007). A survey on wireless multimedia sensor networks. *Computer networks*. 51(4), 921-960.
- Akyildiz, I. F., Pompili, D. and Melodia, T. (2004). Challenges for efficient communication in underwater acoustic sensor networks. *ACM Sigbed Review*. 1(2), 3-8.
- Alam, M. J. and O'Shaughnessy, D. (2011). Perceptual improvement of Wiener filtering employing a post-filter. *Digital Signal Processing*. 21(1), 54-65.
- An, E. (2011). *Underwater Channel Modeling for Sonar Applications*, MSc Thesis, The Graduate School of Natural and Applied Sciences of Middle East Technical University.
- Assous, S., Humeau, A., Tartas, M., Abraham, P. and L'Huillier, J.-P. (2006). S-transform applied to laser Doppler flowmetry reactive hyperemia signals. *Biomedical Engineering, IEEE Transactions on*. 53(6), 1032-1037.



- Brockett, P. L., Hinich, M. and Wilson, G. R. (1987). Nonlinear and non-Gaussian ocean noise. *The Journal of the Acoustical Society of America*. 82(4), 1386-1394.
- Burrowes, G. and Khan, J. Y. (2011). *Short-range underwater acoustic communication networks*. INTECH Open Access Publisher.
- Caley, M. and Duncan, A. (2013). Investigation of underwater acoustic multi-path Doppler and delay spreading in a shallow marine environment. *Acoustics Australia*. 41(1), 20-28.
- Catipovic, J. (1990). Performance limitations in underwater acoustic telemetry. *Oceanic Engineering, IEEE Journal of*. 15(3), 205-216.
- Cella, U. M., Johnstone, R. and Shuley, N. (2009). Electromagnetic wave wireless communication in shallow water coastal environment: theoretical analysis and experimental results. *Proceedings of the 2009 Proceedings of the Fourth ACM International Workshop on UnderWater Networks*: ACM, 9.
- Chen, J., Benesty, J., Huang, Y. and Doclo, S. (2006). New insights into the noise reduction Wiener filter. *Audio, Speech, and Language Processing, IEEE Transactions on*. 14(4), 1218-1234.
- Chi, H., Wang, H., Zhang, M. and Zhao, P. (2012). Time-Frequency Filtering for LFM Based on Time S-Transform and Time Inverse S-Transform *Advances in Electronic Engineering, Communication and Management Vol. 2* (pp. 203-209)Springer.
- Chitre, M. (2006). Underwater acoustic communications in warm shallow water channels. *P. hD. Thesis, National Univeristy of Singapore*.
- Chitre, M., Potter, J. and Heng, O. S. (2004). Underwater acoustic channel characterisation for medium-range shallow water communications. *Proceedings of the 2004 OCEANS'04. MTS/IEEE TECHNO-OCEAN'04*: IEEE, 40-45.
- Chitre, M., Potter, J. R. and Ong, S.-H. (2006a). Optimal and near-optimal signal detection in snapping shrimp dominated ambient noise. *Oceanic Engineering, IEEE Journal of*. 31(2), 497-503.
- Chitre, M. A., Potter, J. R. and Ong, S.-H. (2006b). Optimal and near-optimal signal detection in snapping shrimp dominated ambient noise. *Oceanic Engineering, IEEE Journal of*. 31(2), 497-503.

- Chitre, M. A., Potter, J. R. and Ong, S.-H. (2006c). Optimal and near-optimal signal detection in snapping shrimp dominated ambient noise. *IEEE Journal of oceanic engineering*. 31(2), 497-503.
- Cloutier, M. A. (1995). Optimal Digital Detection of Acoustic Signals in Colored Noise. DTIC Document.
- Coates, R. F. (1989). *Underwater acoustic systems*. Halsted Press.
- Colella, D. (1993). Detection of signals in 1/f noise using wavelets. *Proceedings of the 1993 Aerospace Control Systems, 1993. Proceedings. The First IEEE Regional Conference on: IEEE*, 151-155.
- Conover, W. J. and Conover, W. (1980). Practical nonparametric statistics.
- Da Costa, J. P. C., Liu, K., So, H. C., Schwarz, S., Haardt, M. and Römer, F. (2013). Multidimensional prewhitening for enhanced signal reconstruction and parameter estimation in colored noise with Kronecker correlation structure. *Signal Processing*. 93(11), 3209-3226.
- Das, M. and Ari, S. (2013). Analysis of ECG signal denoising method based on S-transform. *IRBm*. 34(6), 362-370.
- De Rango, F., Veltri, F. and Fazio, P. (2012). A multipath fading channel model for underwater shallow acoustic communications. *Proceedings of the 2012 Communications (ICC), 2012 IEEE International Conference on: IEEE*, 3811-3815.
- Donoho, D. L. (1995). De-noising by soft-thresholding. *Information Theory, IEEE Transactions on*. 41(3), 613-627.
- Donoho, D. L. and Johnstone, J. M. (1994). Ideal spatial adaptation by wavelet shrinkage. *Biometrika*. 81(3), 425-455.
- Etter, P. C. (1991). Underwater Acoustic Modeling: Principles, Techniques and Application. *London and New York: Elsevier Applied Science*.
- Etter, P. C. (2013). *Underwater acoustic modeling and simulation*. CRC Press.
- Everest, F. A., Young, R. W. and Johnson, M. W. (1948). Acoustical characteristics of noise produced by snapping shrimp. *The Journal of the Acoustical Society of America*. 20(2), 137-142.
- Fei, Y., Xiao-Yang, L., Qian, W. and En, C. (2014). Underwater Acoustic Communication Based on Hyperbolic Frequency Modulated M-ary Binary Orthogonal Keying. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 12(10), 7311-7317.

- Fisher, F. and Simmons, V. (1977). Sound absorption in sea water. *The Journal of the Acoustical Society of America*. 62(3), 558-564.
- Forchini, G. (2008). The distribution of the sum of a normal and at random variable with arbitrary degrees of freedom. *Metron*. 66(2), 205.
- Forney Jr, F. D. (1998). Acoustic noise removal by combining wiener and wavelet filtering techniques. DTIC Document.
- Foss, S., Korshunov, D. and Zachary, S. (2013). Heavy-Tailed and Long-Tailed Distributions *An Introduction to Heavy-Tailed and Subexponential Distributions* (pp. 7-42)Springer.
- Ghani, K. A., Dimyati, K., Sha'ameri, A. Z. and Daud, N. G. N. (2016). STATISTICAL MODELLING FOR MISSING AND SPURIOUS PULSES IN PULSE REPETITION INTERVAL (PRI) ANALYSIS. *SCIENCE & TECHNOLOGY RESEARCH INSTITUTE FOR DEFENCE*. 18.
- Govindan, S. M., Duraisamy, P. and Yuan, X. (2014). Adaptive wavelet shrinkage for noise robust speaker recognition. *Digital Signal Processing*. 33, 180-190.
- Guo, G. and Mandal, M. (2011). An adaptive stochastic-resonance-based detector and its application in watermark extraction. *WSEAS Transactions on Signal Processing*. 7(2), 65-81.
- Guo, G., Mandal, M. and Jing, Y. (2012). A robust detector of known signal in non-Gaussian noise using threshold systems. *Signal Processing*. 92(11), 2676-2688.
- Gupta, A. K. and Penafiel, M. (1986). Digital whitening of band-limited white noise in the presense of colored noise. *Acoustics, Speech and Signal Processing, IEEE Transactions on*. 34(3), 621-623.
- Gupta, H. R. and Mehra, R. Power Spectrum Estimation using Welch Method for various Window Techniques.
- H. R. Gupta and R. Mehra (2013). Power Spectrum Estimation using Welch Method for various Window Techniques. *International Journal of Scientifc Research Enginering & Technology (IJSRET)*. Vol. 2 (6), pp. 389-392.
- Hartmann, W. M. (1996). Signals, sound, and sensation (Modern Acoustics and Signal Processing). AIP Press.
- Hassanpour, H., Zehtabian, A. and Sadati, S. (2012). Time domain signal enhancement based on an optimized singular vector denoising algorithm. *Digital Signal Processing*. 22(5), 786-794.

- Haykin, S. (2008). *Communication systems*. John Wiley & Sons.
- He, C., Xing, J., Li, J., Yang, Q. and Wang, R. (2015). A new wavelet threshold determination method considering interscale correlation in signal denoising. *Mathematical Problems in Engineering*. 2015.
- Hernand, J.-P. and Roderick, W. I. (1993). Acoustic model-based matched filter processing for fading time-dispersive ocean channels: Theory and experiment. *Oceanic Engineering, IEEE Journal of*. 18(4), 447-465.
- Hernandez, J. R., Amado, M. and Perez-Gonzalez, F. (2000). DCT-domain watermarking techniques for still images: detector performance analysis and a new structure. *Image Processing, IEEE Transactions on*. 9(1), 55-68.
- Hill, P. R., Achim, A., Bull, D. R. and Al-Mualla, M. E. (2014). Dual-tree complex wavelet coefficient magnitude modelling using the bivariate Cauchy-Rayleigh distribution for image denoising. *Signal Processing*. 105, 464-472.
- Hodges, R. P. (2011). *Underwater acoustics: Analysis, design and performance of sonar*. John Wiley & Sons.
- Hošťálková, E. and Procházka, A. (2006). Wavelet signal and image denoising. *Proceedings of the 2006 14th annual conference technical computing prague*.
- Jensen, F. B. (1994). *Computational ocean acoustics*. Springer Science & Business Media.
- Jing-yi, L., Hong, L., Dong, Y. and Yan-sheng, Z. (2016). A New Wavelet Threshold Function and Denoising Application. *Mathematical Problems in Engineering*. 2016.
- Johnstone, I. M. and Silverman, B. W. (1997). Wavelet threshold estimators for data with correlated noise. *Journal of the royal statistical society: series B (statistical methodology)*. 59(2), 319-351.
- Kalpana, G., Rajendran, V. and Murugan, S. S. (2014). Study of de-noising techniques for SNR improvement for underwater acoustic communication. *Journal of Marine Engineering & Technology*. 13(3), 29-35.
- Kassam, S. A. (2012). *Signal detection in non-Gaussian noise*. Springer Science & Business Media.
- Kay, S. (2000). Can detectability be improved by adding noise? *IEEE Signal Processing Letters*. 7(1), 8-10.
- Kay, S. M. (1998a). Fundamentals of statistical signal processing, Vol. II: Detection Theory. *Signal Processing. Upper Saddle River, NJ: Prentice Hall*.

- Kay, S. M. (1998b). *Fundamentals of Statistical signal processing, Volume 2: Detection theory*. Prentice Hall PTR.
- Kay, S. M. (2013). *Fundamentals of statistical signal processing: Practical algorithm development*. (Vol. 3) Pearson Education.
- Kilfoyle, D. B. and Baggeroer, A. B. (2000). The state of the art in underwater acoustic telemetry. *Oceanic Engineering, IEEE Journal of*. 25(1), 4-27.
- King, P., Venkatesan, R. and Li, C. (2008). An improved communications model for underwater sensor networks. *Proceedings of the 2008 Global Telecommunications Conference, 2008. IEEE GLOBECOM 2008. IEEE: IEEE*, 1-6.
- Kishk, M. A. and Alaa, A. M. (2014). On the capacity of the underwater acoustic channel with dominant noise sources. *Proceedings of the 2014 Telecommunication Technologies (ISTT), 2014 IEEE 2nd International Symposium on: IEEE*, 183-187.
- Kumar, S., Kumar, P., Gupta, M. and Nagawat, A. K. (2010). Performance comparison of median and Wiener filter in image de-noising. *International Journal of Computer Applications*. 12(4).
- Levy, B. C. (2008). *Principles of signal detection and parameter estimation*. Springer Science & Business Media.
- Lilliefors, H. W. (1969). On the Kolmogorov-Smirnov test for the exponential distribution with mean unknown. *Journal of the American Statistical Association*. 64(325), 387-389.
- Liu, Y., Zhou, W., Li, P., Yang, S. and Tian, Y. (2016). An Ultrahigh Frequency Partial Discharge Signal De-Noising Method Based on a Generalized S-Transform and Module Time-Frequency Matrix. *Sensors*. 16(6), 941.
- Lukac, R., Smolka, B. and Plataniotis, K. N. (2007). Sharpening vector median filters. *Signal Processing*. 87(9), 2085-2099.
- M. L. a. W. Zhao (2012.). Review Article On 1/f Noise. *Hindawi Publishing Corporation Mathematical Problems in Engineering*,. Volume 2012,(Article ID 673648).
- Machell, F. W., Penrod, C. S. and Ellis, G. E. (1989). Statistical characteristics of ocean acoustic noise processes *Topics in non-Gaussian signal processing* (pp. 29-57) Springer.

- Mallat, S. G. (1989). A theory for multiresolution signal decomposition: the wavelet representation. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*. 11(7), 674-693.
- McLoughlin, I. (2009). *Applied speech and audio processing: with Matlab examples*. Cambridge University Press.
- Medwin, H. and Clay, C. S. (1997). *Fundamentals of acoustical oceanography*. Academic Press.
- Mei, C. Y., Sha'ameri, A. Z. and Boashash, B. (2012). Efficient phase estimation for the classification of digitally phase modulated signals using the cross-WVD: a performance evaluation and comparison with the S-transform. *EURASIP Journal on Advances in Signal Processing*. 2012(1), 1-22.
- Melodia, T., Kulhandjian, H., Kuo, L.-C. and Demirors, E. (2013). Advances in underwater acoustic networking. *Mobile Ad Hoc Networking: Cutting Edge Directions*. 804-852.
- Middleton, D. (1987). Channel modeling and threshold signal processing in underwater acoustics: An analytical overview. *IEEE Journal of Oceanic Engineering*. 12(1), 4-28.
- Montgomery-Smith, S. J. and Pruss, A. R. (2001). A comparison inequality for sums of independent random variables. *Journal of mathematical analysis and applications*. 254(1), 35-42.
- Moreaud, U., Courmontagne, P., Ouelha, S., Chaillan, F. and Mesquida, J.-R. (2014). Underwater acoustic signal denoising Using multi-directionnals masks on time-frequency representation. *Proceedings of the 2014 OCEANS 2014-TAIPEI*: IEEE, 1-8.
- Murugan, S. S., Natarajan, V. and Kumar, R. R. (2012). Estimation of noise model and denoising of wind driven ambient noise in shallow water using the LMS algorithm. *Acoustics Australia*. 40(2), 111.
- Naidu, P. S. (2009). *Sensor array signal processing*. CRC press.
- Nason, G. P. (2006). On the sum of t and Gaussian random variables. *Statistics & probability letters*. 76(12), 1280-1286.
- Ngo, K., Van Waterschoot, T., Christensen, M. G., Moonen, M. and Jensen, S. H. (2013). Improved prediction error filters for adaptive feedback cancellation in hearing aids. *Signal Processing*. 93(11), 3062-3075.

- Nguyen, T. and Liao, Y. (2009). Power quality disturbance classification utilizing S-transform and binary feature matrix method. *Electric Power Systems Research*. 79(4), 569-575.
- Nielsen, P. and Thomas, J. (1989). Non-parametric detection in underwater environments. *Proceedings of the 1989 Acoustics, Speech, and Signal Processing, 1989. ICASSP-89., 1989 International Conference on:* IEEE, 2728-2731.
- Nikias, C. L. and Shao, M. (1995). *Signal processing with alpha-stable distributions and applications*. Wiley-Interscience.
- Nixon, M. (2008). *Feature extraction & image processing*. Academic Press.
- Olkkonen, H. (2011). Discrete wavelet transforms: Algorithms and applications. *InTech, August*.
- Oppenheim, A. V. and Verghese, G. C. (2010). Signals, systems, and inference. *Class notes for*. 6.
- Panaro, J., Lopes, F., Barreira, L. M. and Souza, F. E. (2012). Underwater Acoustic Noise Model for Shallow Water Communications. *Proceedings of the 2012 Brazilian Telecommunication Symposium*,
- Panaro, J. S., Lopes, F. R., Barreira, L. M. and Souza, F. E. Underwater Acoustic Noise Model for Shallow Water Communications.
- Peebles, P. Z., Read, J. and Read, P. (2001). *Probability, random variables, and random signal principles*. (Vol. 3)McGraw-Hill New York.
- Pei, S.-C., Wang, P.-W., Ding, J.-J. and Wen, C.-C. (2011). Elimination of the discretization side-effect in the S transform using folded windows. *Signal Processing*. 91(6), 1466-1475.
- Pinnegar, C. R. and Eaton, D. W. (2003a). Application of the S transform to prestack noise attenuation filtering. *Journal of Geophysical Research: Solid Earth (1978–2012)*. 108(B9).
- Pinnegar, C. R. and Eaton, D. W. (2003b). Application of the S transform to prestack noise attenuation filtering. *Journal of Geophysical Research: Solid Earth*. 108(B9).
- Pinnegar, C. R. and Mansinha, L. (2003). The S-transform with windows of arbitrary and varying shape. *Geophysics*. 68(1), 381-385.
- Powell, D. R. and Wilson, G. R. (1989). Class A modeling of ocean acoustic noise processes *Topics in Non-Gaussian Signal Processing* (pp. 17-28)Springer.

- Prasanth, K. P. (2004). Modelling and simulation of an underwater acoustic communication channel. *Master, Electronic Engineering University of applied sciences, Bremen, Germany.*
- Proakis, J. G. (1996). Digital signal processing: principles, algorithms, and application-3/E.
- Raj, K. M., Murugan, S. S., Natarajan, V. and Radha, S. (2011). Denoising algorithm using wavelet for underwater signal affected by wind driven ambient noise. *Proceedings of the 2011 Recent Trends in Information Technology (ICRTIT), 2011 International Conference on: IEEE*, 943-946.
- Rioul, O. and Vetterli, M. (1991). Wavelets and signal processing. *IEEE signal processing magazine*. 8(LCAV-ARTICLE-1991-005), 14-38.
- Roopa, S. and Narasimhan, S. (2014). S-transform based on analytic discrete cosine transform for time–frequency analysis. *Signal Processing*. 105, 207-215.
- Roth, E. H., Hildebrand, J. A., Wiggins, S. M. and Ross, D. (2012). Underwater ambient noise on the Chukchi Sea continental slope from 2006–2009. *The Journal of the Acoustical Society of America*. 131(1), 104-110.
- SAOUD, S., BOUSSELMI, S., NASER, M. B. and CHERIF, A. (2016). New Speech Enhancement based on Discrete Orthonormal Stockwell Transform. *International Journal of Advanced Computer Science & Applications*. 1(7), 193-199.
- Schimmel, M. and Gallart, J. (2005). The inverse S-transform in filters with time-frequency localization. *Signal Processing, IEEE Transactions on*. 53(11), 4417-4422.
- Sha'ameri, A. Z., Al-Aboosi, Y. and Khamis, N. H. H. (2014). Underwater Acoustic Noise Characteristics of Shallow Water in Tropical Seas. *Proceedings of the 2014 Computer and Communication Engineering (ICCCE), 2014 International Conference on: IEEE*, 80-83.
- Sharma, A. and Sharma, S. (2014). Comparison of denoising techniques for Underwater Acoustic Signals. *International Journal of Advanced Research in Computer and Communication Engineering*. Vol. 3 (Issue 5).
- Shukla, S. and Tiwari, A. K. (2013). *Efficient Algorithms for Discrete Wavelet Transform: With Applications to Denoising and Fuzzy Inference Systems*. Springer Science & Business Media.



- Sklar, B. (2002). Digital Communications: Fundamentals and Applications. BEIJING: Publishing House of Electronics Industry.
- Skolnik, M. I. (2001). RADAR systems. McGraw-Hill, NY.
- Srivastava, M., Anderson, C. L. and Freed, J. H. (2016). A new wavelet denoising method for selecting decomposition levels and noise thresholds. *IEEE Access*. 4, 3862-3877.
- Stockwell, R. G., Mansinha, L. and Lowe, R. (1996). Localization of the complex spectrum: the S transform. *Signal Processing, IEEE Transactions on*. 44(4), 998-1001.
- Stojanovic, M. (2003). Acoustic (underwater) communications. *Encyclopedia of Telecommunications*.
- Stojanovic, M. (2007). On the relationship between capacity and distance in an underwater acoustic communication channel. *ACM SIGMOBILE Mobile Computing and Communications Review*. 11(4), 34-43.
- Stojanovic, M. (2008). Underwater acoustic communications: Design considerations on the physical layer. *Proceedings of the 2008 Wireless on Demand Network Systems and Services, 2008. WONS 2008. Fifth Annual Conference on: IEEE*, 1-10.
- Stojanovic, M. and Preisig, J. (2009). Underwater acoustic communication channels: Propagation models and statistical characterization. *Communications Magazine, IEEE*. 47(1), 84-89.
- Syed, A. A. and Heidemann, J. S. (2006). Time Synchronization for High Latency Acoustic Networks. *Proceedings of the 2006 INFOCOM*,
- Symons Jr, F. W. (1981). Use of linear prediction in detecting narrowband signals in colored noise. *Proceedings of the 1981 Acoustics, Speech, and Signal Processing, IEEE International Conference on ICASSP'81.: IEEE*, 279-282.
- Therrien, C. W. (1992). *Discrete random signals and statistical signal processing*. Prentice Hall PTR.
- Thorp, W. H. (1967). Analytic Description of the Low-Frequency Attenuation Coefficient. *The Journal of the Acoustical Society of America*. 42(1), 270-270.
- Tsihrintzis, G. A. and Nikias, C. L. (1995a). Performance of optimum and suboptimum receivers in the presence of impulsive noise modeled as an

- alpha-stable process. *IEEE Transactions on communications*. 43(2/3/4), 904-914.
- Tsihrintzis, G. A. and Nikias, C. L. (1995b). Performance of optimum and suboptimum receivers in the presence of impulsive noise modeled as an alpha-stable process. *Communications, IEEE Transactions on*. 43(2/3/4), 904-914.
- Tucker, J. D. and Azimi-Sadjadi, M. R. (2010). Neyman Pearson detection of K-distributed random variables. *Proceedings of the 2010 SPIE Defense, Security, and Sensing: International Society for Optics and Photonics*, 76640Q-76640Q-76612.
- Urick, R. J. (1967). *Principles of underwater sound for engineers*. Tata McGraw-Hill Education.
- Urick, R. J. (1983). The noise background of the sea: ambient noise level. *Principles of Underwater Sound. Peninsula Publishing, Los Altos, California*. 202-236.
- Urick, R. J. (1984). Ambient noise in the sea. DTIC Document.
- Ventosa, S., Simon, C., Schimmel, M., Dañobeitia, J. J. and Mànuel, A. (2008). The-transform from a wavelet point of view. *Signal Processing, IEEE Transactions on*. 56(7), 2771-2780.
- Wang, J., Huang, J., Jiao, Y. and Zhang, Q. (2011). Adaptive matched filter detection method on underwater small aperture array. *Proceedings of the 2011 Statistical Signal Processing Workshop (SSP), 2011 IEEE: IEEE*, 97-100.
- Wang, Y. (2011). Efficient stockwell transform with applications to image processing.
- Wegman, E. J., Schwartz, S. C. and Thomas, J. B. (2012). *Topics in non-Gaussian signal processing*. Springer Science & Business Media.
- Wei, G., Yang, C. and Chen, F.-j. (2011). Closed-form frequency estimator based on narrow-band approximation under noisy environment. *Signal Processing*. 91(4), 841-851.
- Widrow, B. and Walach, E. (2008). *Adaptive Inverse Control A Signal Processing Approach*. Reissue edn. John Wiley & Sons, Inc.
- Xiaohong, S., Haiyan, W., Yuzhi, Z. and Ruiqin, Z. (2012). *Adaptive technique for underwater acoustic communication*. INTECH Open Access Publisher.
- Xie, W., Zhang, Q., Chen, Y. and Xie, W. (1999). Detection of known signals in 1/f fractal noise. *Journal of Electronics (China)*. 16(2), 152-158.

- Xu, Y., Weaver, J. B., Healy Jr, D. M. and Lu, J. (1994). Wavelet transform domain filters: a spatially selective noise filtration technique. *Image Processing, IEEE Transactions on*. 3(6), 747-758.
- Yang, J., Cheng, Y., Wang, H., Li, Y. and Hua, X. (2015). Unknown stochastic signal detection via non-Gaussian noise modeling. *Proceedings of the 2015 Signal Processing, Communications and Computing (ICSPCC), 2015 IEEE International Conference on: IEEE*, 1-4.
- Yi, J. and Peng, J. (2009). Power quality disturbances denoising using modified s-transform. *Proceedings of the 2009 Sustainable Power Generation and Supply, 2009. SUPERGEN'09. International Conference on: IEEE*, 1-5.
- Yu, S. K., Kim, W. T. and Joo, E. K. (2006). Optimum Signal Detector in Non-white Noise. *Proceedings of the 2006 ICN/ICONS/MCL*, 152.
- Zhang, Q., Wang, L. and Sun, W. (2012). Signal denoising with average sampling. *Digital Signal Processing*. 22(2), 226-232.
- Zhang, X. and Xiong, Y. (2009). Impulse noise removal using directional difference based noise detector and adaptive weighted mean filter. *Signal Processing Letters, IEEE*. 16(4), 295-298.
- Zhao, M. L. a. W. (2012). Review Article On 1/f Noise. *Hindawi Publishing Corporation Mathematical Problems in Engineering Volume 2012, Article ID 673648, 23 pages doi:10.1155/2012/673648*.
- Zhou, Z., Hua, D., Wang, Y., Yan, Q., Li, S., Li, Y. and Wang, H. (2013). Improvement of the signal to noise ratio of Lidar echo signal based on wavelet de-noising technique. *Optics and Lasers in Engineering*. 51(8), 961-966.