



Matched Doppler Processing

Stephen Searle

Thesis submitted for partial requirements for the degree of
Master of Applied Science

Dept. of Electrical and Electronic Engineering

Faculty of Engineering

University of Adelaide

South Australia

August 1997

Contents

List of Figures	vi
List of Tables	vii
Abstract	ix
Publications	xi
Statement of Originality	xiii
Acknowledgements	xv
1 Introduction	1
1.1 Analysis of Source Motion	1
1.2 Thesis Outline	5
1.3 Summary of Contributions	6
2 Background	9
2.1 Estimation Theory	9
2.2 The Doppler Effect and Source Tracking	10
2.3 Coherent Processing	12

2.4	Matched Filtering	13
2.5	Beamforming	15
2.6	Matched Processing	17
2.6.1	Matched Field Processing	18
3	Matched Doppler Tracking	21
3.1	Problem Model	21
3.2	Signal Model	22
3.2.1	Effect of Time-lag on Signal Phase	22
3.2.2	Received Amplitude	23
3.2.3	Instantaneous Frequency	23
3.2.4	Manifestation of Time-lag as a Doppler Shift	24
3.2.5	Model of Received Signal	25
3.2.6	Replica Measurements	25
3.2.7	Signal Measurement	27
3.3	Matching Functions	29
3.3.1	EST Cost Function	29
3.3.2	EST Cost Function with Phase Information	29
3.3.3	CBF-style Correlation Function	30
3.3.4	Phase Cost Function	30
3.3.5	Ambiguity Surfaces	31
3.3.6	Similarity of A&P and CBF Cost Functions	35
3.4	Simulations	38

3.4.1	Data Generation	38
3.4.2	Simulation 1	38
3.4.3	Simulation 2	39
3.4.4	Discussion	44
3.5	Summary	47
4	Bounds on Estimator Variance	49
4.1	The Cramer–Rao Lower Bound on Range Estimates	49
4.2	Bounds Imposed by the Discrete Nature of the Domain	50
4.2.1	Variance on a Discrete Uniformly Spaced Interval	50
4.2.2	Quantisation Noise	51
4.3	Actual Bounds on Simulations	51
5	Robustness Issues	57
5.1	Effect of Range Perturbation on Signal Phase	57
5.2	Model for Range Perturbation	58
5.3	Signal Model with Range Perturbations	58
5.4	Robustness Simulations	59
5.5	Summary	62
6	Application to Real Data	63
7	Multiple Receivers	67
7.1	Geometry of the Problem	68
7.2	Spatially Incoherent Method	69

7.3	Spatially Coherent Method	71
7.4	Simulations	75
7.4.1	Simulation Details	75
7.4.2	Discussion	87
7.4.3	Summary and Extensions	90
8	Conclusion	91
8.1	Summary	91
8.2	Extensions	93
A	Derivation of Cramer–Rao Lower Bounds	95
	Bibliography	99

List of Figures

2.1	Phasor representation of signal $A \exp i(\omega t + \phi)$	14
2.2	Incoherent and Coherent Combination of Signal Phasors	14
3.1	Source at time t'	22
3.2	Components Of Target Velocity	24
3.3	Effect of Doppler shift on Fourier bin	26
3.4	The Matching Process	28
3.5	EST Cost Function Ambiguity Surface	33
3.6	Amp & Phase Cost Function Ambiguity Surface	33
3.7	CBF Ambiguity Surface	34
3.8	Phase Only Ambiguity Surface	34
3.9	A&P Cost Function, Exact Phase Known.	37
3.10	Bias in Range Estimates	40
3.11	Standard Deviation in Range Estimates	40
3.12	Bias in \hat{r}_i & \hat{r}_f , relative to \hat{r}_{cpa}	41
3.13	Standard deviation of \hat{r}_i & \hat{r}_f , relative to \hat{r}_{cpa}	41
3.14	Doppler tracks of 5 replicas with different r_{cpa}	46
3.15	Doppler tracks of 5 replicas with different r_{cpa} , high velocity	46

4.1	Bounds on r_{cpa} estimator variance, ϕ -only	53
4.2	Bounds on r_{cpa} estimator variance, ϕ -only with quantisation errors	53
4.3	Bounds on r_{cpa} estimator variance, A&P	55
4.4	Bounds on r_{cpa} estimator variance, A&P, fine domain	55
6.1	Measured Amp & Phase with replica, low freq 1	65
6.2	Measured Amp & Phase with replica, low freq 2	65
6.3	Measured Amp & Phase with replica, hi freq	66
7.1	Spatially Incoherent Matched Processing with K Receivers	70
7.2	All Candidate Trajectories for Simulated Data Analysis	77
7.3	All Candidate Trajectories for Simulated Data Analysis with Two Sources	77

List of Tables

3.1	Bias & std. deviation in all range estimates	42
3.2	Bias in \hat{r}_i & \hat{r}_f , relative to \hat{r}_{cpa}	43
3.3	Bias & Standard Deviation for Simulation 2	43
5.1	Bias & std deviation in estimates of wobbly track	61
5.2	Bias & std deviation in estimates of wobbly track, longer sample	61
7.1	Bias, Varying Number Of Receivers	79
7.2	Standard Deviation, Varying Number Of Receivers	80
7.3	Bias, Varying Hydrophone Separation	81
7.4	Standard Deviation, Varying Hydrophone Separation	82
7.5	2 Sources In Domain, Spatially-Coherent cost function	83
7.6	2 Sources, Only 1 In Domain, Spatially-Incoherent cost function	84
7.7	2 Sources In Domain, Spatially-Incoherent cost function	85
7.8	2 Sources, Only 1 In Domain, Spatially-Coherent cost function	86

Abstract

This thesis describes a method for estimating the ranges and speed of a nearfield narrowband sound source as it moves past a receiver. This is applied to analysis of source motion in the underwater acoustic environment.

The technique correlates or “matches” the receiver output with a large set of replicas. A replica is generated for each combination of possible candidate source ranges and speeds. These replicas are generated according to a simple propagation model which takes into account the doppler effects inherent in the motion of the theoretical source.

Particular emphasis is placed upon the treatment of signal phase. This is carefully modelled in the replica by considering the differential time-lag and DFT cell distortion induced by the doppler effect. The matching functions exploit this phase information by processing it coherently.

The matched processing algorithm is tested with both simulated data and real data from a sonobuoy. Performance bounds of the estimators are derived and discussed in context with the simulation results. It is shown that the phase-coherent matching functions satisfy these bounds. The robustness of the technique to variance in the source trajectory is investigated through further simulation.

The technique is extended to perform tracking of source range, azimuth, speed and heading with the use of multiple receivers. A matching function which processes phase coherently across space as well as time is presented. This is compared to a spatially-incoherent formulation via extensive simulation.

Publications

- S.J. Searle & D.A. Gray, “Environmental Source Tracking and the Doppler Shift”, presented at ISSPA-96, August 26-28, 1996.
- S.J. Searle & D.A. Gray, “Matched Doppler Processing for Estimating Moving Source Parameters”, submitted to the Journal of the Acoustical Society of America, April 1997.

Statement of Originality

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

SIGNED:

DATE:

13/2/98

Acknowledgements

The author wishes to thank the following people and organisations:

- Prof. Barry Quinn, for providing the opportunity and initial motivation to undertake postgraduate study.
- Prof. Doug Gray, for his “expert and highly competent supervision” and his unwaning enthusiasm for the research.
- The various other students supervised by Doug Gray for their discussions and support. Particular thanks go to John Legg for much useful discussion about the Cramer–Rao lower bound.
- The Co–Operative Research Centre for Robust and Adaptive Systems for providing funding to support this study.
- The Co–Operative Research Centre for Sensor Signal and Information Processing for providing resources with which to pursue research.
- Various members of Maritime Operations Division, DSTO Salisbury, including Dr. John Riley, Dr. Lesley Kelly, Dr Shane Tonissen; for useful discussions and access to real data.
- Dr. Alan Bolton from MRD, DSTO Salisbury for the interest shown in this work and some insightful discussion.

- Dr. Jane Perkins (MOD) and Dr. Michael Greening for support provided within the workplace and for being a willing audience on which to practice oratory skills.
- Finally, Dr. Peter Kootsookos who, unbeknownst to himself, taught the author more than he ever wanted to know about \LaTeX by leaving some source code on the MOD machines.

The author wishes to acknowledge the funding of the activities of the two aforementioned Co-Operative Research Centres by the Australian Government under the Co-Operative Research Centre Program.