Fast and Unambiguous Direction Finding for Digital Radar Intercept Receivers

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Doctor of Philosophy

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For my wife, Joy

The Light of my Life

Contents

List of Figures

List of Tables

Abstract

This thesis considers the problem of angle-of-arrival (AOA) estimation in the context of its application to electronic surveillance systems. Due to the operational requirements of such systems, the AOA estimation algorithm must be computationally fast, accurate and will need to be implemented using sparse, large aperture arrays.

Interferometry is proposed as a suitable algorithm that meets the operational requirements of electronic surveillance systems. However, for sparse array geometries, phase wrapping effects introduce ambiguities to the phase measurements and so unambiguous AOA estimation requires the use of computationally intensive ambiguity resolution algorithms using three or more antennas.

Beamforming and array processing techniques are another class of AOA estimation algorithms that can unambiguously estimate the AOA using sparse, large aperture arrays. While these techniques generally offer better AOA estimation performance than interferometric techniques, they are also comparatively more computationally intensive algorithms. Furthermore, by virtue of using very sparse arrays, high sidelobes in the array beampattern may cause incorrect AOA estimation.

This thesis will introduce the concept of using second-order difference array (SODA) geometries which allow unambiguous AOA estimation to be performed in a computationally efficient manner. In the context of interferometry, the so-called "SODA interferometer" will be shown to synthesise the equivalent output of a smaller virtual aperture to allow unambiguous AOA estimation to be performed at the expense of a coarser estimation performance compared to the physical aperture of the array. It will also be shown that the coarse SODA AOA estimate can be used to cue the conventional ambiguity resolution algorithms to provide higher accuracy in a computationally efficient manner. This thesis will also show that the creation of virtual arrays from SODA geometries can be generalised to a larger number of antennas to allow conventional array processing techniques to perform unambiguous AOA estimation in a computationally fast manner.

The AOA estimation performance of each algorithm is compared through simulations and also verified using experimental data. This thesis will show that the SODA interferometer, SODA-cued ambiguity resolution algorithms and so-called "second-order array processors" can be used to obtain high accuracy AOA estimates in a more computationally efficient manner than the conventional algorithms.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, 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. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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3 December 2013

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Publications

Some parts of this thesis have been published for presentation at conferences. The following list is the bibliographic information pertaining to these preliminary presentations.

- Ly, P. Q. C., Elton, S. D., Li, J. & Gray, D. A., "Computationally Fast AOA Estimation Using Sparse Large Aperture Arrays for Electronic Surveillance," in *Proceedings of the IEEE International Conference on Radar (RADAR 2013)*, 2013. Accepted.
- Ly, P. Q. C., Elton, S. D., Gray, D. A., & Li, J., "Unambiguous AOA Estimation Using SODA Interferometry for Electronic Surveillance," in *Proceedings of the IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM 2012)*, pp. 277–280, 2012.
- Ly, P. Q. C., Gray, D. A., Elton, S. D., & Bates, B. D., "A Digital Interferometric Testbed for ES/ELINT Research," in *Proceedings of the Seventh Direction Finding and Geolocation Symposium*, 2008.

Acronyms

Acronym	Description
ADC	Analogue to Digital Converter
AOA	Angle of Arrival
CAS	Common Angle Search
CBF	Conventional Phaseshift Beamforming
COS	Correlative Interferometry using the Cosine Cost Function
CRLB	Cramér-Rao Lower Bound
CW	Continuous Wave
DOA	Direction of Arrival
DF	Direction Finding
DFT	Discrete Fourier Transform
DSTO	Defence Science and Technology Organisation
ELINT	Electronic Intelligence
ES	Electronic Support
ESM	Electronic Support Measures
EW	Electronic Warfare
FFT	Fast Fourier Transform
FMCW	Frequency Modulated Continuous Wave
FOV	Field of View
FPGA	Field Programmable Gate Array
GSPS	Giga-Samples Per Second, 1×10^9 Samples Per Second
LPI	Low Probability of Intercept
LS	Correlative Interferometry using the Least Squares Cost Function
MSPS	Mega-Samples Per Second, 1×10^6 Samples Per Second
MLE	Maximum Likelihood Estimator
MSE	Mean Square Error
MUSIC	Multiple Signal Classification
POI	Probability of Intercept
PRI	Pulse Repetition Interval
RMS	Root Mean Square
RMSE	Root Mean Square Error
RWR	Radar Warning Receiver
SBI	SODA-Based Inference
SNR	Signal to Noise Ratio
SODA	Second Order Difference Array
TDC	Time to Digital Converter
TDOA	Time Difference of Arrival
TOA	Time of Arrival
TOB	Time of Burst

Notation

Symbols

The following symbols will be used throughout this thesis:

Symbol	Description
η	Signal to Noise Ratio
A	Peak Amplitude of the Signal
f	Carrier Frequency of the Signal
λ	Wavelength of the Signal's Carrier Frequency
φ	Initial Phase of the Signal
θ	Azimuth Component of the Signal's Angle of Arrival
ϕ	Elevation Component of the Signal's Angle of Arrival
t_s	Sample Interval
f_s	Sampling Rate (or Sampling Frequency)
τ	Propagation Time Delay Between Two Antennas
ψ	Propagation Phase Delay Between Two Antennas
d	Distance Between Two Antennas (or Interferometer Baseline)
t	Time Instance
$s(t)$	Continuous Time-Varying Signal Without Noise
$x(t)$	Continuous Time-Varying Signal With Noise
$\epsilon(t)$	Continuous Time Additive Gaussian Noise
$s[n]$	Discrete Time-Varying Signal Without Noise
$x[n]$	Discrete Time-Varying Signal With Noise
$\epsilon[n]$	Discrete Time Additive Gaussian Noise
$\beta(\theta)$	Phase Error due to Channel Imbalance
N	Number of Samples
K	Number of Antennas
M	Number of Interferometer Baselines
D	Set of Interferometer Baselines
Υ	Set of Potential Ambiguity Numbers for a Single Baseline
Ω	Set of Ambiguity Number Combinations from all Baselines
σ	Standard Deviation of Noise
$v(\theta)$	Propagation Delay for a Single Baseline
$\boldsymbol{v}(\theta)$	Propagation Delay Vector for all Baselines
$\Delta\theta$	Azimuth Grid Search Resolution
$\mathrm{BW}_{\mathrm{NN}}$	Null-to-Null Beamwidth

Scripts and Accents

Scripts and accents will be used to confer additional meaning to the above symbols.

- A single letter subscript specifies that the associated parameter belongs to a specific hardware channel. For example, A_k and f_k refers to the peak amplitude and carrier frequency of the k-th receiver channel. A single letter subscript can also specify that the parameter belongs to a particular interferometric baseline. For example, ψ_m and d_m refers to the phase delay and baseline of the m-th interferometer baseline. When only a single letter subscript is used, it is generally implied that the specified parameter refers to an arbitrary interferometer baseline.
- A double letter subscript specifies the parameter of a particular channel with respect to another channel. For example, ψ_{kl} and d_{kl} refers to the phase delay and interferometer baseline of the k-th antenna relative to the l-th antenna. When a double letter subscript is used, it is generally implied that the specified parameter refers to a specific interferometer baseline.
- The subscript $_s$ specifies a steered parameter that is under the control of the radar intercept receiver. For example, θ_s refers to the steered AOA of a grid search algorithm for AOA estimation.
- The superscript ^{u} specifies an uncalibrated parameter that is subject to channel imbalances.
- The superscript ^{c} specifies a calibrated parameter free of channel imbalances.
- The tilde accent $\tilde{}$ specifies a measured parameter. In particular, when specifying the phase delay measurement, ψ refers to the unwrapped, unambiguous phase delay, however, $\tilde{\psi}$ refers to the measured, ambiguous phase delay that is constrained to the interval $[-\pi, \pi]$.
- The hat accent $\hat{}$ specifies an estimated parameter.
- Plain typeface symbols, e.g. $v(\theta)$, are used to denote scalar variables.
- Bold typeface symbols in lower case characters, e.g. $\boldsymbol{v}(\theta)$, are used to denote vector variables.
- Bold typeface symbols in upper case characters, e.g. $\boldsymbol{R}$, are used to denote matrix variables.

Mathematical Operators

Operator	Description
round $[a]$	Rounds the scalar a to the nearest integer.
$\lceil a \rceil$	Rounds the scalar a upwards to the next integer.
$\lfloor a \rfloor$	Rounds the scalar a downwards to the next integer.
$\odot$	Cartesian product.
$\boldsymbol{a}^T$ or $\boldsymbol{A}^T$	Transpose of the vector, $\boldsymbol{a}$, or matrix, $\boldsymbol{A}$.
$\boldsymbol{a}^H$ or $\boldsymbol{A}^H$	Hermitian (complex conjugate) transpose of the vector, $\boldsymbol{a}$, or matrix, $\boldsymbol{A}$.

Units

All parameters are assumed to adhere to the International System of Units (or SI units).

The units of phase-related values, such as the phase delay and angle-of-arrival, are assumed to be expressed in radians for all mathematical expressions. However, for readability, the phase-related values will often be expressed in degrees in the text and figures.