Large Scale Antenna Array for GPS Bistatic Radar

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Contents

Abstract

GPS passive bistatic radar uses signals transmitted by navigation satellites to perform target detection. This research aims to develop a ground-based receiver that detects the reflected GPS signals from air targets. The main challenge for GPS bistatic radar is the difficulty in detecting the extremely weak power GPS signal reflections from a target since GPS satellites are located at very high altitudes and transmit signals at relatively low power levels.

The research in this thesis investigates the minimum power of the reflected GPS signal that can be reliably detected by applying several techniques for enhancing the receiver detection performance. The proposed techniques for GPS bistatic radar target detection model include: using a large scale antenna array at the receiver, applying long coherent integration times for the captured data and non-coherently summing the power returns of targets from multiple satellites or receivers. This detection model requires the radar system to incorporate the signal information from a large number of receiving channels and non-cooperative transmitters to perform air target detection.

This research also incorporates additional techniques at the pre-detection stage that are essential for the target detection model. Among these techniques include: direct-path GPS signals acquisition that obtains the Doppler frequency component and C/A code pattern from each satellite, array calibration that realigns the inter-element phase errors and orientation of phased-array receiver using the GPS system, and direct-path signal interference cancellation.

The GPS bistatic radar target detection performance was initially investigated using the results produced by computer simulations. Then, a prototype phased-array GPS bistatic radar receiver was built to capture target reflections from an aircraft and investigate the detection performance of the system experimentally. The system was able to successfully detect and locate the position of a nearby aircraft, which demonstrates that the techniques introduced for GPS bistatic radar in this thesis do work in practice. The experimental results also provide a benchmark that can be used to estimate the scale of the receiver required for detecting objects at a greater distance.

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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Signature:

Date:

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Abbreviations

2-D/3-D	Two/Three-dimensional space
ADC	Analogue-to-digital converter
ARM	Anti-radiation missile
AWGN	Additive white Gaussian noise
BCAF	Cross ambiguity function (Beamformer)
BDS	BeiDou navigation satellite system
BPSK	Binary phase-shift keying
C/A	Coarse/acquisition
CAF	Cross ambiguity function
CCAF	Cross ambiguity function (Combined elements)
CDF	Cumulative distribution function
CDMA	Code division multiple access
CFAR	Constant false alarm rate
CRPA	Controlled radiated pattern antenna
CW	Continuous wave
DAB	Digital audio broadcasting
DOA	Direction-of-arrival
DOP	Dilution of precision
DSI	Direct-path signal interference
DSP	Digital signal processor
DSSS	Direct-sequence spread spectrum
DVB-S	Digital video broadcasting-Satellite
DVB-T	Digital video broadcasting-Terrestrial
ECM	Electronic countermeasure
EIRP	Effective isotropic radiated power
FDOA	Frequency-difference-of-arrival

FFT	Fast Fourier transform
FIFO	First in, first out
FM	Frequency modulation
FPGA	Field-programmable gate arrays
FRPA	Fixed radiated pattern antenna
GEMS	GNSS environment monitoring system
GNSS	Global navigation satellite system
GPS	Global Positioning System
GSM	Global system for mobile communications
HDOP	Horizontal dilution of precision
IF	Intermediate frequency
JPALS	Joint precision approach and landing system
LEO	Low Earth orbit
LHCP	Left-hand, circularly polarized
LNA	Low noise amplifier
LOS	Line-of-sight
LP	Linearly polarised
LSE	Least squares estimator
MCE	Monte Carlo experiments
MEO	Medium Earth orbit
MIMO	Multiple-input & multiple-output
MISO	Multiple-input & single-output
MMSE	Minimum mean square error
MSE	Mean squared error
MVDR	Minimum variance distortionless response
PBR	Passive bistatic radar
P	Precision
PC	Personal computer
PDF	Probability density function
PDOP	Position dilution of precision
PLL	Phased-locked loop
PMR	Passive MIMO radar
PRN	Pseudo-random noise
RCS	Radar cross-section

RF	Radio frequency
RHCP	Right-hand, circularly polarised
RMSE	Root-mean-square error
SDRAM	Synchronous dynamic random access memory
SISO	Single-input & single-output
SNR	Signal-to-noise ratio
SV	Space vehicle
TBD	Track-before-detect
TDOA	Time-difference-of-arrival
TOA	Time-of-arrival
UERE	User equivalent range error
VDOP	Vertical dilution of precision
VHDL	VHSIC hardware description language
VHSIC	Very high speed integrated circuit

Symbols

x^*	complex conjugate
x^{T}	transpose
x^{H}	Hermitian/conjugate transpose
$f(t)$	continuous function
$f(k)$	discrete function
$n(t)$, $n(k)$	white noise
$\boldsymbol{a}$	array steering vector
b	receiver index
c	speed of light
f_{B}	signal bandwidth
f_0	signal carrier frequency
f_D	direct-path signal Doppler frequency
f_δ	target Doppler frequency
$\not{f}$	function of Doppler frequency
j	complex number
k	sample index
$\mathscr{k}$	Boltzmann constant
$\Bbbk$	data sub-block time frame index
l	transmitter/satellite index
m	antenna element index
$\mathfrak{m}$	multipath signal index
n	noise
$\boldsymbol{p}$	position vector
$\boldsymbol{u}$	coordinate of sensor's element relative to reference
$\boldsymbol{v}$	velocity vector
$\boldsymbol{w}$	weigh vector

B	number of base stations/receiver sites
C(t), C(k)	PRN code sequence
$\mathcal{C}(k, \boldsymbol{p}_\delta)$	function of PRN code sequence
E(H)	expectation of random variable
G	gain
$\mathcal{H}$	hypothesis of a statistical model
I	identity matrix
K	number of samples
$\mathbb{K}$	total number of data sub-blocks
$\bar{K}$	size of each data sub-block
L	number of illuminators/satellites
M	number of antenna elements
$\mathfrak{M}$	number of multipath signals
$\mathcal{N}$	number of Monte Carlo experiments
P_x, P_y, P_z	position search range in x, y and z dimensions
$\mathbb{P}$	probability
$\mathcal{P}$	subspace projection of signals
P_R	receiving power at the receiver
P_T	transmitting power of illuminator
R_D	direct propagation path
R_T	transmitter-to-target/transmission path
R_R	receiver-to-target/reflected path
$\mathcal{R}(t)$, $\mathcal{R}(k)$	Cross-correlation function
RX	receiver
TX	transmitter
V_x, V_y, V_z	velocities search range in x, y and z dimensions
V	velocity magnitude
Γ	Gamma function
Λ	chi-squared distribution non-centrality parameter
α	number of beams
β	bistatic angle
γ	lower incomplete Gamma function
δ	target index

ϵ	inter-element phase error
θ	azimuth angle
λ_0	signal wavelength
ρ	pseudorange
ψ	target velocity aspect angle
μ	signal amplitude
σ	noise amplitude
σ_B	bistatic radar cross section
τ	detection threshold
ϕ	elevation angle

Publications

1. C. Pui, M. Trinkle, "GPS Bistatic Radar Research and Experimental Results", in Progress in Radar Research (PIRR) Workshop, Adelaide, Australia, 2011.
2. C. Pui, M. Trinkle, "GPS Bistatic Radar for Target Detection and Estimation using Antenna Arrays", in International Global Navigation Satellite Systems (IGNSS), Sydney, Australia, 2011.
3. C. Pui, M. Trinkle, "Experimental Results Investigating the Feasibility of GPS Bistatic Radar for Target Detection and Estimation", in Proceedings of the 24th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2011), Portland, OR, September 2011, pp. 3165-3171.
4. C. Pui, M. Trinkle, B. Ng, "Passive Bistatic Radar for Aircraft Detection using GPS as a Source of Opportunity", in Defence Science Institute (DSI) Passive Radar Workshop, Melbourne, Australia, 2013.
5. C. Pui, M. Trinkle, B. Ng, "Aircraft Detection Experimental Results for GPS Bistatic Radar using Phased-array Receiver", in International Global Navigation Satellite Systems (IGNSS), Gold Coast, Australia 2013.
6. C. Pui, M. Trinkle, "GPS Bistatic Radar using Phased-array Technique for Aircraft Detection", in Proceedings of IEEE International Conference on Radar, Adelaide, Australia, 2013, pp. 274-279.
7. C. Pui, M. Trinkle, B. Ng, "Progress in GPS Bistatic Radar for Air Target Detection", in Progress in Radar Research (PIRR) Workshop, Adelaide, Australia, 2014.
8. C. Pui, M. Trinkle, "Aircraft Detection using GPS Bistatic Radar incorporating MIMO Techniques", in IEEE Two-Day Workshop on Passive Radar, Adelaide, Australia, 2015.