

Multichannel Synthetic Aperture Radar

by

Luke Rosenberg

B.E. (Electrical & Electronic, Honours),
The University of Adelaide, Australia, 2000

M.S.I.P (Signal & Information Processing),
The University of Adelaide, Australia, 2002

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The School of Electrical & Electronic Engineering,
The Faculty of Engineering, Computer and Mathematical Sciences
The University of Adelaide, Australia

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Abstract

Synthetic Aperture Radar (SAR) is a coherent imaging technique capable of generating fine resolution images from long stand off ranges, either day or night. The use of multiple antennas for SAR is referred to as multichannel SAR and offers the additional abilities to perform height estimation of the ground, improve the resolution and suppress backscatter and/or undesired interferences.

The first part of this thesis looks at the problem of image formation for a multichannel SAR. Three wavefront reconstruction algorithms are presented based on the multichannel matched filter imaging equation. They demonstrate differing levels of performance and accuracy which will determine their practical use. A fourth algorithm known as multichannel backprojection is then presented to provide comparative quality with the best wavefront reconstruction algorithm with a reduced computational load.

The remainder of the thesis is then focussed on image formation while suppressing undesired interferences. This topic has not received a lot of coverage in the literature as the application is primarily for defence. If present in the mainbeam of a SAR, a jammer can potentially destroy a large region of the SAR image. In addition to this, multipath reflections from the ground, known as hot-clutter or terrain scattered interference will add a non-stationary interference component to the image. The goal of interference suppression for SAR is to suppress these interferences while not significantly effecting the image quality by blurring, reducing the resolution or raising the sidelobe level.

A study into the effect of hot-clutter interference on a SAR image is provided with a comparison of suppression techniques using multichannel imaging, optimal slow and fast-time Space Time Adaptive Processing (STAP). Simulation results indicate that fast-time STAP offers the best potential for suppressing hot-clutter while maintaining a coherent SAR image. Further investigations using a sub-optimal fast-time STAP filter are then presented to determine the best location of the adaptive filter in the SAR processing chain and how to best implement it in the real world. A number of suitable filters are introduced with reduced computational load and rank. They are based on a constrained optimisation criteria and include data-independent methods such as fast-time element and beamspace STAP as well as data-dependent eigen-based methods and the multistage Wiener filter.

Declaration

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 made available in all forms of media, now or hereafter known.

Signed

Date

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Publications

- ROSENBERG-L.** AND **GRAY-D. A.** (2004a). Anti-jamming techniques for multichannel SAR, *European SAR Conference, Ulm, Germany*, pp. 879–882.
- ROSENBERG-L.** AND **GRAY-D. A.** (2004b). Multichannel SAR imaging using wavefront reconstruction, *International Radar Symposium, Warsaw, Poland*, pp. 155–160.
- ROSENBERG-L.** AND **GRAY-D. A.** (2004c). Multichannel SAR imaging with backprojection, *IEEE Conference on Intelligent Sensors, Sensor Networks and Information Processing, Melbourne, Australia*, pp. 265–270.
- ROSENBERG-L.** AND **GRAY-D. A.** (2005a). Fast-time filtering with multichannel SAR, *Adaptive Sensor Array Processing Workshop, Lexington MA, United States of America*. no. 16.
- ROSENBERG-L.** AND **GRAY-D. A.** (2005b). Robust interference suppression for Synthetic Aperture Radar, *IEEE International Symposium on Signal Processing and its Applications, Sydney, Australia*, pp. 883–886.
- ROSENBERG-L.** (2006). Reduced rank fast-time STAP using the multistage Wiener filter in multichannel SAR, *International Radar Symposium, Krakow, Poland*, pp. 97–100.
- ROSENBERG-L.**, **TRINKLE-M.** AND **GRAY-D. A.** (2006). Fast-time STAP performance in pre and post range processing adaption as applied to multichannel SAR, *International Radar Symposium, Krakow, Poland*, pp. 625–628.
- ROSENBERG-L.** AND **GRAY-D. A.** (2006a). Reduced rank interference suppression for multichannel SAR, *European SAR Conference, Dresden, Germany*. no. P6.8.
- ROSENBERG-L.** AND **GRAY-D. A.** (2006b). Anti-jamming techniques for multichannel SAR imaging, *IEE Proceedings of Radar, Sonar and Navigation*, **153**(3), pp. 234–242.
- ROSENBERG-L.** AND **GRAY-D. A.** (2006c). Constrained fast-time STAP techniques for interference suppression in multichannel SAR, *Defence Applications of Signal Processing, Fraser Island, Australia*.

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Geometry

h	Mean height of SAR and jammer platforms above ground (m)
h_p	Height of SAR platform above ground (m)
h_J	Height of jammer platform above ground (m)
ϕ_{3dB}	3 dB antenna beamwidth (rad)
φ	SAR integration angle (rad)
ψ	Grazing angle (rad)
ψ_J	Jammer grazing angle (rad)
R	Radial distance (m)
R_{\min}, R_{\max}	Minimum and maximum radial distances (m)
\bar{R}_J	Radial distance along ground between SAR and jammer (m)
\mathbf{R}_{rot}	Slant plane rotation matrix
$\mathbf{R}_{\text{rot}3}$	Ground plane rotation matrix
$\bar{\theta}_a$	Ground-plane aspect angle (rad)
$\theta_a, \theta_a(x, y)$	Slant-plane aspect angle (rad)
$\theta_{a,k}(u)$	Slant-plane aspect angle (rad)
$\theta, \theta(u)$	Slant-plane aspect angle relative to centre of patch (rad)
θ_J	Jammer offset angle (rad)
ϑ	Elevation angle (rad)
x, x'	Slant range and slant range at broadside (m)
\bar{x}, \bar{x}'	Ground range and ground range at broadside (m)
\bar{x}_J	Ground range between SAR and jammer (m)
X_c	Offset range (m)
$2X_0$	Range swath width (m)
y, \bar{y}	Azimuth (m)
y', \bar{y}'	Azimuth at broadside (m)
$2Y_L$	SAR integration length (m)
$2Y_S$	Synthetic aperture length (m)

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$2Y_0$	Azimuth along track extent (m)
$2Y_W$	Antenna along track extent (m)
$2Y_{W,\min}$	Minimum antenna along track extent (m)
$2Y_{W,\max}$	Maximum antenna along track extent (m)
\bar{z}, \bar{z}'	Ground plane height and ground plane height at broadside (m)

Signal Model - Main Variables

d_n	Antenna offset position (m)
k, k_c	Wavenumber and wavenumber defined at carrier frequency (rad/m)
k_u	Slow-time frequency (rad/m)
k_x	Range spatial frequency (rad/m)
k_{xc}	Centre range spatial frequency (rad/m)
$k_{x,\min}, k_{x,\max}$	Minimum and maximum range spatial frequencies (rad/m)
k_y	Azimuth spatial frequency (rad/m)
$k_{y,\min}, k_{y,\max}$	Minimum and maximum azimuth spatial frequencies (rad/m)
λ, λ_c	Wavelength and wavelength defined at carrier frequency (m)
ω	Fast-time frequency defined at carrier frequency (rad/s)
$\tilde{\omega}$	Fast-time frequency defined at baseband (rad/s)
ω_c	Fast-time carrier frequency (rad/s)
ω_{up}	Upsampled fast-time frequency (rad/s)
s_m	The m^{th} slow-time sample (s)
t_l	The l^{th} fast-time sample (s)
\tilde{t}	Absolute time (s)
t_{up}	Upsampled fast-time (s)
u_m	The m^{th} slow-time spatial sample (m)
\bar{u}_m	The m^{th} slow-time spatial sample over user defined imaging area (m)
$\bar{\mathbf{u}}$	The slow-time spatial vector over user defined imaging area (m)
z	Hot-clutter scattering height autocorrelation variable (m)
ζ	Correlation fast-time variable (s)
$\tilde{\zeta}$	Generic correlation variable (s)

Signal Model - Functions

$\tilde{a}(\omega, x, y)$	Antenna amplitude pattern
$a(x, y)$	Two-way antenna beampattern defined at carrier frequency
$A(k_y)$	Two-way antenna beampattern defined at carrier frequency
$\mathcal{A}(u)$	Modified constraint matrix
$\mathbf{b}(u)$	First column of spatial blocking matrix
$\tilde{\mathbf{b}}(u)$	Non-zero component within first column of spatial blocking matrix
$\mathbf{B}(u), \mathbf{B}_q(u)$	Spatial blocking matrix
$\mathbf{B}_f(u), \mathbf{B}_{f,q}(u)$	Space/fast-time blocking matrix
$C_h(z)$	Hot-clutter scatterer height autocorrelation function
$\mathbf{C}(u)$	Spatial constraint matrix
$\mathbf{C}_{\text{amp}}(u)$	Spatial amplitude constraint matrix
$\mathbf{C}_{\text{deriv1}}(u)$	Spatial first order derivative constraint matrix
$\mathbf{C}_{\text{deriv2}}(u)$	Spatial second order derivative constraint matrix
$\mathbf{C}_{\text{MVDR}}(u)$	Spatial MVDR constraint matrix
$\mathbf{C}_f(u)$	Space/fast-time constraint matrix
\mathbf{d}	Spatial vector of constraining values corresponding to constraint matrix
\mathbf{d}_{amp}	Spatial vector of constraining values corresponding to amplitude constraint matrix
$\mathbf{d}_{\text{deriv1}}$	Spatial vector of constraining values corresponding to first order derivative constraint matrix
$\mathbf{d}_{\text{deriv2}}$	Spatial vector of constraining values corresponding to second order derivative constraint matrix
\mathbf{d}_{MVDR}	Spatial vector of constraining values corresponding to MVDR constraint matrix
\mathbf{d}_f	Space/fast-time vector of constraining values corresponding to constraint matrix
$D(x, y)$	Reference image to be measured in the SDR
\mathbf{e}_k	Spatial zero vector with unity on the k^{th} element
$E(x)$	Generic function used to express Taylor series
$f_s(\xi)$	Probability density function for diffuse scattering model
$F_s(\xi)$	Cumulative density function for diffuse scattering model
$f(x, y)$	Ground return at baseband

List of Symbols

$f(t, u)$	Ground return at baseband
$f(\theta, t, u)$	Ground return at baseband
$\tilde{f}(\omega, u)$	Ground return at baseband
$\tilde{f}(\Theta, F_d, \omega)$	Ground return at baseband
$\tilde{F}(\omega, k_u)$	Ground return at baseband
$F(k_x, k_y)$	Ground return at baseband
$f_n(x, y)$	Ground return at baseband for the n^{th} channel
$f_{sp}, f_{sp}(\theta, t, u)$	Ground return at baseband with spatial only filtering
$f_{sp}(t, u)$	Ground return at baseband with spatial only filtering
$\tilde{f}_{ss}(\omega, u)$	Ground return at baseband with slow-time STAP filtering
$\tilde{F}_{ss}(\omega, k_u)$	Ground return at baseband with slow-time STAP filtering
$\tilde{f}_{ss}(\Theta, F_d, \omega)$	Ground return at baseband with slow-time STAP filtering
$\hat{f}(x, y)$	Estimated ground return at baseband
$\hat{F}(k_x, k_y)$	Estimated ground return at baseband
$\hat{f}_{dB}(x, y)$	Estimated ground return at baseband in dB
$\hat{f}_{RF}(x, y)$	Estimated ground return at the carrier frequency
$\hat{f}_{fs}(x, y)$	Estimated ground return at baseband with fast-time STAP filtering
$\hat{f}_{ss}(x, y)$	Estimated ground return at baseband with slow-time STAP filtering
$\hat{F}_{ss}(k_x, k_y)$	Estimated ground return at baseband with slow-time STAP filtering
$g(t, u)$	Temporal component of target signal
$g_{pre,k}(t)$	Temporal steering signal for the k^{th} fast-time tap, pre RP
$g_{post,k}(t)$	Temporal steering signal for the k^{th} fast-time tap, post RP
\mathbf{g}	Temporal steering vector
\mathbf{g}_{pre}	Temporal steering vector, pre RP
\mathbf{g}_{post}	Temporal steering vector, post RP
$\tilde{\mathbf{G}}(\Theta, F_d)$	Space/slow-time steering vector, stacked space/slow-time
$\tilde{\mathbf{G}}_J(\Theta_J)$	Jammer signal vector, stacked space/slow-time
$\tilde{\mathbf{G}}_T$	Target signal vector, stacked space/slow-time
$\tilde{\mathbf{G}}(\omega, u)$	Space/slow-time steering vector, post RP, stacked space/slow-time
$\gamma(t, u)$	Total ground return at baseband
$\gamma_n(t, u)$	Total ground return at baseband for the n^{th} channel
$\Gamma(\omega)$	Space/time ground return at baseband

$\tilde{\mathbf{I}}$	Total ground return at baseband, stacked space/slow-time
$\mathbf{\Gamma}_f(t, u)$	Total ground return at baseband, stacked space/fast-time
$\gamma_{\text{pre}}(t, u)$	Total ground return at baseband, pre RP
$\gamma_{\text{pre},n}(t, u)$	Total ground return at baseband for the n^{th} channel, pre RP
$\gamma_{\text{pre,RF}}(t, u)$	Total ground return at the carrier frequency, pre RP
$\gamma_{\text{post},n}(t, u)$	Total ground return at baseband for the n^{th} channel, post RP
$\mathbf{h}_q(u)$	Spatial basis vector in MWF
$\mathbf{h}_{f,q}(u)$	Space/fast-time basis vector in MWF
$\tilde{\mathbf{H}}_{\text{pre}}(t, u)$	Space/fast-time steering vector, pre RP, stacked space/fast-time
$H_{\text{post},n}(t, u)$	Space/fast-time steering signal for the n^{th} channel, post RP
$\mathbf{H}(t, u)$	Space/fast-time steering vector, stacked spatially
$\mathbf{H}_{\text{post}}(t, u)$	Space/fast-time steering vector, post RP, stacked spatially
$\tilde{\mathbf{H}}(u)$	Space/fast-time steering vector, stacked space/fast-time
$\tilde{\mathbf{H}}_{\text{post}}(t, u)$	Space/fast-time steering vector, post RP, stacked space/fast-time
$\tilde{\mathbf{H}}_{\text{post}}(u)$	Space/fast-time steering vector, post RP, stacked space/fast-time
$J(\tilde{t}), J(t)$	Jammer waveform
$J(t, u)$	Jammer waveform
$J_s(\omega)$	Space/slow-time jammer waveform
\mathbf{J}	Jammer waveform vector
$\mathcal{J}(\omega, k_u)$	Jacobian function
$\mathbf{L}_Q(u)$	Spatial sequential decomposition vector for the MWF
$\mathbf{L}_{f,Q}(u)$	Space/fast-time sequential decomposition vector for the MWF
L_{SINR}	SINR loss
$\nu(t, u)$	Receiver noise signal at baseband
$\nu_n(t, u)$	Receiver noise signal at baseband for the n^{th} channel
$\Xi(\omega)$	Space/slow-time receiver noise signal
$\nu_{\text{RF}}(t, u)$	Receiver noise signal at the carrier frequency
\mathcal{O}	Complexity function
$p_c(\tilde{t}), p_c(t)$	SAR signal waveform
$P_c(\tilde{\omega})$	SAR signal waveform
$p_t(\tilde{t})$	Transmitted signal
$\phi_n(u)$	Phase signal for the n^{th} channel

List of Symbols

$P, P(\theta)$	Mean output power
$P(\Theta, F_d)$	Mean output power
P_{MVDR}	MVDR mean output power
P_{SINR}	Maximum SINR mean output power
$P_b(\theta)$	Beampattern
$P_b(\Theta, F_d)$	Beampattern
$P_J(\omega)$	Jammer power spectral density
\mathbf{P}_z	Hung Turner projection matrix
$\mathbf{r}, \mathbf{r}_1, \mathbf{r}_2$	Random Gaussian vectors used for jammer waveform realisation
$r_J(\tilde{\zeta})$	Jammer autocorrelation signal
\mathbf{r}_J	Jammer autocorrelation vector
$\mathbf{r}_{x_q, e_{q'}}(u)$	Reference beam interference plus noise spatial cross covariance
$\mathbf{r}_{f, x_q, e_{q'}}(u)$	Reference beam interference plus noise space/fast-time cross covariance
$\mathbf{R}_{x_q}(u)$	Reference beam interference plus noise spatial covariance matrix
$\mathbf{R}_{f, x_q}(u)$	Reference beam interference plus noise space/fast-time covariance matrix
$\mathbf{R}_x(u)$	Total received spatial covariance matrix
$\mathbf{R}_z(u)$	Interference plus noise spatial covariance matrix
$\hat{\mathbf{R}}_z(u)$	Estimated interference plus noise spatial covariance matrix
$\hat{\mathbf{R}}'_z(u)$	Normalised estimated interference plus noise spatial covariance matrix
$\hat{\mathbf{R}}_{z, \text{DL}}(u)$	Normalised estimated interference plus noise spatial covariance matrix with diagonal loading
$\mathbf{R}_{\tilde{z}}$	Interference plus noise space/slow-time covariance matrix
$\mathbf{R}_{\tilde{z}_c}$	Interference plus ground clutter plus noise space/slow-time covariance matrix
$R_{Z_f, \text{pre}}(t, \zeta, \cdot)$	Interference space/fast-time instantaneous covariance element, pre RP
$\tilde{R}_{Z_f, \text{pre}}(\zeta, \cdot)$	Interference space/fast-time mean estimated covariance element, pre RP
$R_{Z_f, \text{post}}(t, \zeta, \cdot)$	Interference space/fast-time instantaneous covariance element, post RP
$\tilde{R}_{Z_f, \text{post}}(\zeta, \cdot)$	Interference space/fast-time mean estimated covariance element, post RP
$\hat{\mathbf{R}}_{Z_f}, \hat{\mathbf{R}}_{Z_f}(u)$	Estimated interference plus noise space/fast-time covariance matrix
$\hat{\mathbf{R}}'_{Z_f}(u)$	Normalised estimated interference plus noise space/fast-time covariance matrix
$\hat{\mathbf{R}}_{Z_f, \text{DL}}(u)$	Normalised estimated interference plus noise space/fast-time covariance matrix with diagonal loading
$s_n(u)$	Spatial signal model for the n^{th} channel

$s_n(\theta), s_n(\Theta)$	Spatial signal model for the n^{th} channel
$s_n(u, \delta_{\text{amp}})$	Spatial signal model for the n^{th} channel
$\mathbf{s}(\theta), \mathbf{s}(u)$	Spatial steering vector, stacked spatially
$s_{\text{pre}}(t, u, \cdot)$	Signal model, pre RP
$s_{\text{pre},n}(t, u, \cdot)$	Signal model for the n^{th} channel, pre RP
$\mathbf{s}_{\text{pre}}(t, u, \cdot)$	Signal model vector, pre RP, stacked spatially
$s_{\text{post}}(t, u, \cdot)$	Signal model, post RP
$s_{\text{post},n}(t, u, \cdot)$	Signal model for the n^{th} channel, post RP
$\mathbf{s}_{\text{post}}(t, u, \cdot)$	Signal model vector, post RP, stacked spatially
$\tilde{s}_{\text{post}}(\omega, u, \cdot)$	Signal model, post RP
$\tilde{s}_{\text{post},n}(\omega, u, \cdot)$	Signal model for the n^{th} channel, post RP
$\tilde{\mathbf{s}}_{\text{post}}(\omega, u, \cdot)$	Signal model vector, post RP, stacked spatially
$S_{\text{post}}(\omega, k_u, \cdot)$	Signal model, post RP
$S_{\text{post},n}(\omega, k_u, \cdot)$	Signal model for the n^{th} channel, post RP
$\mathbf{S}_{\text{post}}(\omega, k_u, \cdot)$	Signal model vector, (ω, k_u) domain, post RP, stacked spatially
$\tilde{s}_{\text{ref},n}(\omega, u)$	Signal model reference signal for the n^{th} channel
$\tilde{\mathbf{s}}_{\text{ref}}(\omega, u)$	Signal model reference vector, post RP, stacked spatially
$S_{\text{ref},n}(\omega, k_u)$	Signal model reference signal for the n^{th} channel
$\mathbf{S}_{\text{ref}}(\omega, k_u)$	Signal model reference vector, stacked spatially
$\mathbf{s}_{\text{MF}}(t)$	Matched filter reference vector, stacked spatially
$S_{\text{RS},n}(\omega, k_u, x)$	Range stacking reference signal model for the n^{th} channel
$\mathbf{S}_{\text{RS}}(\omega, k_u, x)$	Range stacking reference vector, post RP, stacked spatially
$s_{\text{TDC}}(t, u)$	Time domain correlation reference signal
\mathbf{s}_T	Target signal vector, stacked spatially
$S_{\text{INR}}(\theta)$	Signal to interference plus noise ratio
$T_{\text{d},n}(\theta)$	Spatial time delay for the n^{th} channel
$\tau(x, y)$	Temporal only reflection delay
$\tau_n(x, y)$	Space-time reflection delay for the n^{th} channel
$\tilde{\tau}_n(x, y)$	Spatial only reflection delay for n^{th} channel
$\bar{\tau}_n(x_k, y_k), \bar{\tau}_{n,k}$	Space-time bistatic reflection delay for the k^{th} scatterer and n^{th} channel
$\mathbf{U}(u)$	Reduced rank transform
$\mathbf{U}_{\text{PC}}(u)$	Principle component reduced rank transform

List of Symbols

$\mathbf{U}_{\text{CSM}}(u)$	Cross spectral metric reduced rank transform
$\mathbf{w}(u), \mathbf{w}(\theta)$	Weight vector, stacked spatially
$\mathbf{W}(\theta, F_d)$	Weight vector, stacked space/slow-time
$\mathbf{W}_f(t, u)$	Weight vector, stacked space/fast-time
$\mathbf{w}_a(u)$	Adaptive weight vector, stacked spatially
$\mathbf{W}_{f,a}(u)$	Adaptive weight vector, stacked space/fast-time
$\mathbf{w}_{a,q}(u)$	Adaptive weight vector for the MWF, stacked spatially
$\mathbf{W}_{f,a,q}(u)$	Adaptive weight vector for the MWF, stacked space/fast-time
$\mathbf{w}_d(u)$	Desired weight vector, stacked spatially
$\mathbf{W}_{f,d}(u)$	Desired weight vector, stacked space/fast-time
$\mathbf{W}_{\text{eq}}(u)$	Equivalent non-transformed reduced rank weight vector, stacked space/fast-time
$\mathbf{w}_{\text{conv}}(\theta)$	Conventional weight vector, stacked spatially
$\mathbf{W}_{\text{conv}}(\Theta, F_d)$	Conventional weight vector, stacked space/slow-time
$\mathbf{w}_{\text{MVDR}}(\theta)$	MVDR weight vector, stacked spatially
$\mathbf{W}_{\text{MVDR}}(\Theta, F_d)$	MVDR weight vector, stacked space/slow-time
$\mathbf{w}_{\text{SINR}}(\theta)$	Maximum SINR weight vector, stacked spatially
$\mathbf{W}_{\text{SINR}}(\Theta, F_d)$	SINR weight vector, stacked space/slow-time
$\mathbf{w}_{\text{GSC}}(u)$	GSC weight vector, stacked spatially
$\mathbf{W}_{f,\text{GSC}}(u)$	GSC weight vector, stacked space/fast-time
$\mathbf{w}_{\text{LCMV}}(u)$	LCMV weight vector, stacked spatially
$\mathbf{W}_{f,\text{LCMV}}(u)$	LCMV weight vector, stacked space/fast-time
$\mathbf{w}_{\text{MWF}}(u)$	MWF weight vector, stacked spatially
$\mathbf{W}_{f,\text{MWF}}(u)$	MWF weight vector, stacked space/fast-time
$x(t, u)$	Total received SAR signal at baseband
$x_n(t, u)$	Total received SAR signal at baseband for the n^{th} channel
$\mathbf{x}(t, u)$	Total received SAR vector at baseband, stacked spatially
$\tilde{x}_n(\omega, u)$	Total received SAR signal at baseband
$\tilde{\mathbf{x}}(\omega, u)$	Total received SAR vector at baseband, stacked spatially
$X_n(\omega, k_u)$	Total received SAR signal at baseband for the n^{th} channel
$\mathbf{X}(\omega, k_u)$	Total received SAR vector at baseband, stacked spatially
$\tilde{\mathbf{X}}_s(\omega)$	Total received SAR vector at baseband, stacked space/slow-time

$\mathbf{X}_f(u), \mathbf{X}_f(t, u)$	Total received SAR vector at baseband, stacked space/fast-time
$x_{\text{pre}}(t, u)$	Total received SAR signal at baseband, pre RP
$x_{\text{pre},n}(t, u)$	Total received SAR signal at baseband for the n^{th} channel, pre RP
$x_{\text{pre,RF}}(t, u)$	Total received SAR signal at the carrier frequency
$x_{\text{post},n}(t, u)$	Total received SAR signal at baseband for the n^{th} channel, post RP
$x_f(t, u)$	Total received SAR signal at baseband after space/fast-time MF
$x_{\text{fs}}(t, u)$	Total received SAR signal at baseband after fast-time STAP
$x_{\text{ideal}}(t, u)$	Total received SAR signal at baseband with no interference present
$\bar{x}_n(t, u)$	Total received up-sampled SAR signal at baseband for the n^{th} channel
$\bar{x}_{\text{RF},n}(t, u)$	Total received up-sampled SAR signal at the carrier frequency for the n^{th} channel
$\mathbf{x}_q(t, u)$	Total received SAR vector at baseband for GSC, MWF algorithms, stacked spatially
$y_b(\Theta, F_d)$	Output beampattern signal
y_s	Output target signal post adaptive filtering
y_z	Output interference signal post adaptive filtering
$Y(x, y)$	Degraded image to be measured in the SDR
$z(t, u)$	Interference plus noise signal
$z_n(t, u)$	Interference plus noise signal for the n^{th} channel
$\mathbf{z}(t, u)$	Interference plus noise vector, stacked spatially
$\tilde{\mathbf{Z}}_s(\omega)$	Interference plus noise vector, stacked space/slow-time
$\mathbf{Z}_f(u), \mathbf{Z}_f(t, u)$	Interference plus noise vector, stacked space/fast-time
$z_{\text{pre},n}(t, u)$	Interference plus noise signal for the n^{th} channel, pre RP
$z_{\text{post},n}(t, u)$	Interference plus noise signal for the n^{th} channel, post RP
$z_{\text{dp},n}(t, u)$	Direct-path jamming signal for the n^{th} channel
$z_{\text{hc},n}(t, u)$	Hot-clutter jamming signal for the n^{th} channel
$z_{\text{spat},n}(t, u)$	Spatial component of interference plus noise signal for the n^{th} channel
$\mathbf{z}_{\text{spat}}(t, u)$	Spatial component of interference plus noise vector, stacked spatially
$z_{\text{temp}}(t, u)$	Temporal component of interference plus noise signal
$z_{\text{tran}}(\tilde{t})$	Transmitted jamming signal
$z_{c,n}(t, u)$	Interference plus ground clutter plus noise signal
$\tilde{\mathbf{Z}}_c(\omega)$	Interference plus ground clutter plus noise vector, stacked space/slow-time

Signal Model - Parameters and Other Variables

2α	Chirprate (rad/s)
α_{norm}	Normalising level for spatial interference plus noise covariance
$\alpha_{\text{f,norm}}$	Normalising level for space/fast-time interference plus noise covariance
α_{s}	Scale factor to constrain scatterer amplitudes in diffuse scattering model (dB)
α_T	Output target signal power (dB)
b_k	Relative magnitude between the direct-path and k^{th} hot-clutter scatterer (dB)
\tilde{b}_k	Antenna amplitude voltage for the k^{th} scatterer (V)
B	Bandwidth (Hz)
B_c	Pulse compressed bandwidth (Hz)
B_f	Fractional bandwidth
B_x, B_y	Range and azimuth mainlobe 3dB level in spatial frequency domain (rad/m)
β	Angle made by the bisector of the hot-clutter incident and scattered rays with the \bar{z} -axis (rad)
β_0	Upper β limit which defines hot-clutter scattering contour boundary (rad)
$\tilde{\beta}$	Relationship between normalised slow-time Doppler rate and steering angles. This parameter determines the slope of the clutter ridge in the $\Theta - F_d$ domain.
c	Speed of light (m/s)
C	Number of eigen-pairs used in reduced rank GSC
δ	Antenna spacing (m)
δ_{amp}	Amplitude constraint offset angle (rad)
D_y	Antenna length (m)
Δ	Small number used in Taylor series
$\Delta f_{k,k'}$	Differential Doppler shift between two scatterers (Hz)
Δ_t	Fast-time sampling rate (s)
Δ_x	Spatial (range) sampling rate (m)
Δ_X	3dB range resolution (m)
Δ_y	Distance travelled between pulses / slow-time (azimuth) sampling rate (m)
Δ_Y	3dB azimuth resolution (m)
$\Delta\omega_{k,k'}$	Differential Doppler shift between two scatterers (rad/s)
e_q, \hat{e}_q	Indicates paths in the GSC and MWF algorithms
η	Diagonal loading level (dB)

ϵ	Dielectric constant (Fm^{-1})
ε	Random variable used for CDF in diffuse scattering model (rad)
f_d	Slow-time Doppler rate (Hz)
f_{PRF}	Pulse Repetition Frequency (Hz)
F_d	Normalised slow-time Doppler
$F_{d,T}$	Normalised target Doppler
G_r	Receiver gain (dB)
G_t	Transmitter gain (dB)
$\tilde{\gamma}$	Normalising coefficient for the maximum SINR weight vector
$\tilde{\Gamma}$	Fresnel reflection coefficient (dB)
$\tilde{\Gamma}_h, \tilde{\Gamma}_v$	Fresnel reflection coefficient for horizontal and vertical polarisations (dB)
I_x, I_y	Number of pixels in imported image
κ_k	The k^{th} eigenvalue
K_β	Surface roughness parameter
K_{av}	Number of averages used to test jammer autocorrelation
K_{gc}	Number of ground patches included in ground clutter simulation model
K_{hc}	Number of hot-clutter ground patches included in jammer model
L	Number of fast-time samples
\tilde{L}	Number of fast-time taps
L_P	Number of range bins used in transmitted pulse, TP
L_t	Number of range bins used for covariance estimation
L_{up}	Number of upsampled fast-time samples
L_I	Ideal number of fast-time taps
L_J	The total length of the jammer signal realisation
L_Z	Number of zeros used in upsampling
Λ	Singular value/eigenvector decomposition component vector
M	Number of pulses or slow time samples
M'	Number of pulses used for estimating covariance in optimal fast-time STAP
M_f	Number of focus positions used in ground clutter model
M_{max}	Maximum number of pulses chosen for simulation cases
μ	Angle used to express differences in height for the diffuse scattering model (rad)
n_x, n_y	Number of range and azimuth pixels in final image

List of Symbols

N	Number of antenna channels or spatial samples
N_{con}	Number of constraints
$\omega_{\text{d}}, \omega_{\text{d},k}$	General Doppler shift and for the k^{th} scatterer (rad/s)
P_{over}	Azimuth over-sampling rate for simulation scenarios 2 and 3
P_{r}	Received power (dB)
P_{t}	Transmitted power (dB)
Q	MWF maximum order
Q_{sub}	Azimuth subsampling rate for simulation scenario 1
\mathbf{q}_k	The k^{th} eigenvector
$\tilde{\mathbf{Q}}$	Eigenvector decomposition matrix
ρ	Relative power between direct-path and hot-clutter signal components (dB)
s_k	CSM ranking criteria
σ_{h}	Hot-clutter scattering height standard deviation (m)
σ_k	Hot-clutter ground return for the k^{th} scatterer (dB)
σ_{v}^2	Thermal noise power/variance (dB)
σ_{q}^2	Quantisation noise power/variance (dB)
σ_{r}^2	Ground clutter power/variance (dB)
σ_{J}^2	Jammer power/variance (dB)
σ_{T}^2	Target signal power/variance (dB)
Σ	Scattering coefficient (m^2)
$S_{\text{NR,opt}}$	Optimum signal to noise ratio (dB)
$S_{\text{NR,T}}$	Target signal to noise ratio (dB)
T	Fast-time sampling period (s)
T_{f}	Fast-time sampling finish time (s)
T_{I}	Maximum temporal delay between hot-clutter scatterers (s)
T_{L}	Total SAR integration time (s)
T_{p}	Pulse width (s)
T_{PRI}	Pulse Repetition Interval (s)
T_{s}	Fast-time sampling start time (s)
T_{x}	Range swath echo time period (s)
θ_{J}	Jammer signal DOA relative to broadside (rad)
Θ_{J}	Normalised jammer signal DOA relative to broadside

θ_{lim}	Angular slow-time limit (rad)
θ_T	Target signal DOA relative to broadside (rad)
Θ_T	Normalised target signal DOA relative to broadside
Θ	Normalised slow-time steering angle
$\tilde{\mathbf{U}}$	Singular value decomposition component vector
v_p	SAR platform speed along azimuth direction (m/s)
\mathbf{v}_p	SAR platform velocity (m/s)
\mathbf{v}_J	Jammer platform velocity (m/s)
$\tilde{\mathbf{V}}$	Singular value decomposition component vector
x_{ML}	Half mainlobe width of point spread function (m)
ξ	Angle used to define contour in diffuse scattering model (rad)
ξ_A, ξ_B	Limits of ξ used to define the contour limits in the diffuse scattering model (rad)
z_h	Correlation distance for hot-clutter scattering autocorrelation function (m)
Z_r	Impedance at receiver (Ω)
Z_{rat}	Upsampling rate

Other Functions and Operators

$b(x)$	Rectangle function defined over $0 \leq x \leq 1$
$\text{rect}(x)$	Rectangle function defined over $-0.5 \leq x \leq 0.5$
$\text{sinc}(x)$	Sinc function defined as $\sin[\pi x] / \pi x$
$\mathbf{0}_N$	Zero function of size $N \times N$
\mathbf{I}_N	Identity function of size $N \times N$
\rightarrow	Unit vector
$\hat{}$	Estimate
T	Transpose
H	'Hermitian' complex transpose
\dagger	Moore Penrose psuedo inverse
$\mathcal{C}^{N \times M}$	Matrix is complex with size $N \times M$
$E \{ \}$	Expected value
$\mathcal{F} \{ \}$	Fourier transform
$\mathcal{F}^{-1} \{ \}$	Inverse Fourier transform
$*$	Convolution operator
\otimes	Kronecker product

Glossary

List of Acronyms

2D, 3D	Two or Three Dimensional
ATI	Along Track Interferometry
CPI	Coherent Processing Interval
CFAR	Constant False Alarm Rate
CSM	Cross Spectral Metric
DOA	Direction of Arrival
DPCA	Displaced Phase Centre Array
DRFM	Digital Radio Frequency Memory
ERP	Effective Radiated Power
GPS	Global Position Satellite
GSC	Generalised Sidelobe Canceller
FFT	Fast Fourier Transform
FM	Frequency Modulation
FPGA	Field Programmable Gate Array
GLRT	Generalised Likelihood Ratio Test
IFFT	Inverse Fast Fourier Transform
INU	Inertial Navigation Unit
ISLR	Integrated Sidelobe Ratio
JNR	Jammer to Noise Ratio
LCMV	Linearly Constrained Minimum Variance
MF	Matched Filter
MSAR	Multichannel Synthetic Aperture Radar
MSE	Mean Square Error
MTI	Moving Target Indication
MVDR	Minimum Variance Distortionless Response
MWF	Multistage Wiener Filter
PC	Principle Components

Glossary

RCS	Radar Cross Section
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval
PSD	Power Spectral Density
PSF	Point Spread Function
PSR	Peak Sidelobe Ratio
RF	Radio Frequency
RINR	Residual Interference plus Noise Ratio
SAR	Synthetic Aperture Radar
SDR	Signal Distortion Ratio
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
STAP	Space Time Adaptive Processing
TDC	Time Domain Correlation
TSI	Terrain Scattered Interference
WVD	Wigner-Ville Distribution

Nominal Radio Frequency Bands

HF	3 MHz - 30 MHz
VHF	30 MHz - 300 MHz
UHF	300 MHz - 1 GHz
P-band	300 MHz - 350 MHz
L-band	1 GHz - 2 GHz
S-band	2 GHz - 4 GHz
C-band	4 GHz - 8 GHz
X-band	8 GHz - 12 GHz
Ku-band	12 GHz - 18 GHz
K-band	18 GHz - 27 GHz
Ka-band	27 GHz - 40 GHz
V-band	40 GHz - 75 GHz
W-band	75 GHz - 110 GHz
mm-band	110 GHz - 300 GHz