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UCL

Coherent simulation of sea-clutter for a scanning radar

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DST GROUP Science and Technology for Safeguarding Australia

Airborne maritime surveillance

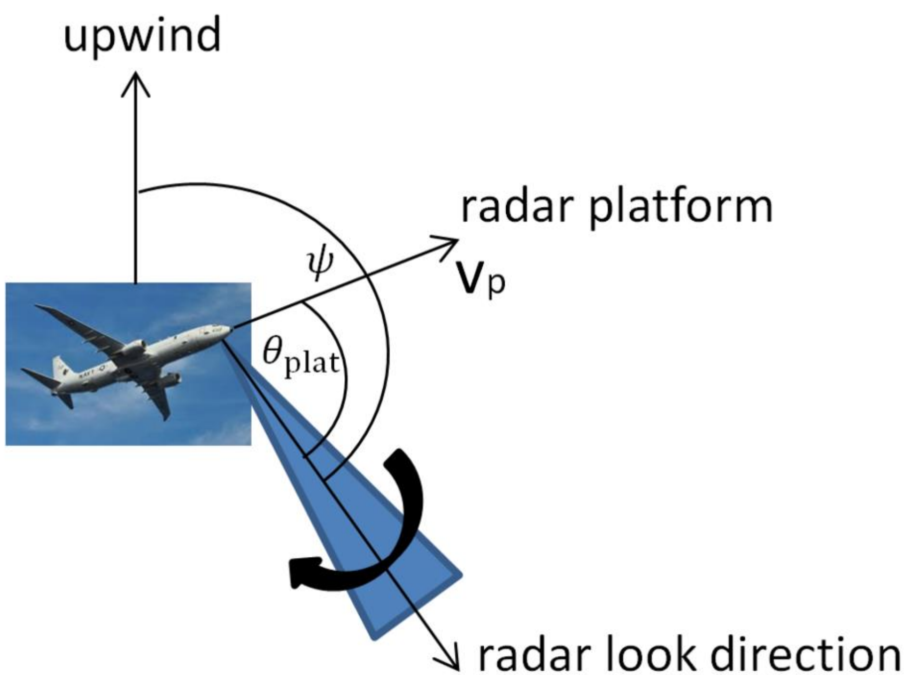
- Detection of small targets on the sea surface
  - Currently operate airborne platforms at low altitude.
  - Low grazing angles have reduced clutter backscatter.
  - Non-coherent processing.
  - Single aperture systems.
- Desire to operate with platforms at higher altitudes.
  - UAVs flying at > 10,000 ft.
- Future radars will likely be multi-aperture and use coherent processing.
- Most clutter simulation techniques only consider a single look direction.
- Need scanning simulation method to help with design and testing of new single and multiple aperture detection schemes.

Background

- Significant work over past years to improve sea-clutter modelling techniques.
- Time and spatially varying Doppler spectra model developed by Watts for low grazing angle clutter (2010).
- Found to be consistent with the Ingara medium grazing angle dataset and extended to a bi-modal model for better representing sea-spikes (2014).
- Adapted to work with the Pareto and K+Rayleigh distributions (2014).
- Model was also extended to include multiple phase centres with a single look direction (2014).
- Parameter models developed to enable generic simulation of original and bi-modal Doppler spectrum models (2015).
- Spectrum model is now used to model the sea-clutter observed from a multi-phase centre scanning radar (2016).

Scanning radar scenario

- Scanning radar platform travelling with velocity, v_p.
- Radar look angle is θ_{plat} , angle relative to wind direction is ψ.
- Assume medium grazing angle scenario to utilise existing Doppler parameter models.



Evolving Doppler spectrum model

- Spectrum model is a single Gaussian with normalised underlying mean (texture), τ:

$$G_0(f,\tau,s,\boldsymbol{\Omega}) = \frac{\tau}{\sqrt{2\pi}s(\boldsymbol{\Omega})}\exp\left[-\frac{(f-m_{\mathrm{f}}(\tau,\boldsymbol{\Omega}))^2}{2s(\boldsymbol{\Omega})^2}\right]$$

- Mean Doppler is related to the normalised texture: $m_{\mathrm{f}}(\tau,\boldsymbol{\Omega}) = A(\boldsymbol{\Omega}) + B(\boldsymbol{\Omega})\tau + f_{\mathrm{plat}}$
- Doppler shift due to moving platform: $f_{\mathrm{plat}} = {}^{2v_p}/_{\lambda}\cos\theta_{\mathrm{plat}}$
- The spectral width, s, is modelled as a Gaussian RV with mean, m_s and std. deviation, σ_s.
- Parameter models required for: A, B, m_s and σ_s.
- Modelled with parameters contained in the set $\boldsymbol{\Omega} = \{\theta_{\mathrm{plat}}, \psi, \theta_{\mathrm{swell}}, \eta, U, H_{1/3}\}$.
- Azimuth two-way beampattern, $\mathrm{A}(\theta)$ related to $\mathrm{A}(f)$ by $f = {}^{2v_p}/_{\lambda}\sin\theta$, width is a function of look angle, $\sin(\theta_{\mathrm{plat}})$ – maximum when side looking.
- Can model spreading due to azimuth two-way beampattern through the convolution:

$$G(f,\tau,s,\boldsymbol{\Omega}) = A(f) * G_0(f,\tau,s,\boldsymbol{\Omega})$$

Simulation method

- Simulation method based on the convolution of the desired clutter impulse response g (order N) and the compound Gaussian model $x\sqrt{\tau}$:

$$\mathrm{y}(\mathrm{m},\tau) = \frac{1}{\sqrt{2}} \sum_{n=-N/2}^{N/2} g(n,\tau,s,\boldsymbol{\Omega})\mathrm{x}(\mathrm{m}+\mathrm{n})\sqrt{\tau(m+n)} \qquad (1)$$

- Texture, τ, modelled with a Gamma distribution with Gaussian (spatial) correlation – produces K-distributed clutter model for $\mathrm{y}(\mathrm{m},\tau)$.
- Speckle, x, modelled as complex normal RV.
- Discretised impulse response, g found by taking Fourier transform of spectral model where f_r is the PRF:

$$g(n,\tau,s,\boldsymbol{\Omega}) = A\left(\frac{n}{f_r}\right)\exp\left[-\mathrm{j}\,\frac{m_f(\tau,\boldsymbol{\Omega})2\pi n}{f_r}\right]\exp[-(2\pi s(\boldsymbol{\Omega})nf_r)^2]$$

- Can be implemented as a sliding window by repeating (1) for each pulse.

Simulation steps

1. Simulate the normalised texture over the entire scan.
   - Only generate realisations for a small number of positions ~ 10 (need approx. constant texture over filter integration time).
   - Distribution shape and spatial decorrelation length determined by user defined inputs in $\boldsymbol{\Omega}$ (sea-state, wind and swell direction, grazing angle).
   - Interpolate to the correct time scale (pulse repetition interval).
2. Generate realisations of the speckle RV, x and the spread RV, *s* (but no scaling or offset).
   - For each pulse, extract correct texture samples from the previous step.
   - Determine model parameters: *A*, *B*, m_s and σ_s.
   - Scale and offset the RV *s*.
   - Form the impulse response *g* and perform convolution.
   - Add thermal noise with the correct CNR (determined by radar range equation and IRSG-linear mean backscatter model).

Parameter modelling

- Parameter model provides a basis for modelling the statistical parameters in the simulation:
- Used for each polarisation channel independently and contains distinct models for **geometry and sea-state**.
- Geometry variation modelled with Fourier series:
  - $X(\eta, \psi) = a_0 \eta^{\gamma} [1 + a_1 \cos\psi + a_2 \cos(2\psi) + a_3 \cos(\psi - \phi) + a_4 \cos(2(\psi - \phi))]$
  - η is the grazing angle, ψ is the azimuth angle,
  - ϕ is the wind swell direction,
  - γ, a_0,…, a_4 are the model coefficients.
- Sea-state variation modelled with:
  - $Y = b_0 + b_1 \log_{10}(U) + b_2 H_{1/3}$, (2)
  - *U* is the wind speed, $H_{1/3}$ is the significant wave height,
  - b_0, b_1, b_2 are the model coefficients.

Parameter modelling

- To relate these two models, coefficients are altered to be independent of grazing angle by introducing a normalisation factor, η_0 and then redefining previous equation:

$$X(\theta,\psi) = \left(\frac{\eta}{\eta_0}\right)^{\gamma} [\alpha_0 + \alpha_1 \cos\psi + \alpha_2 \cos(2\psi) + \alpha_3 \cos(\psi - \phi) + \alpha_4 \cos(2(\psi - \phi)]$$

where the new coefficients are related by

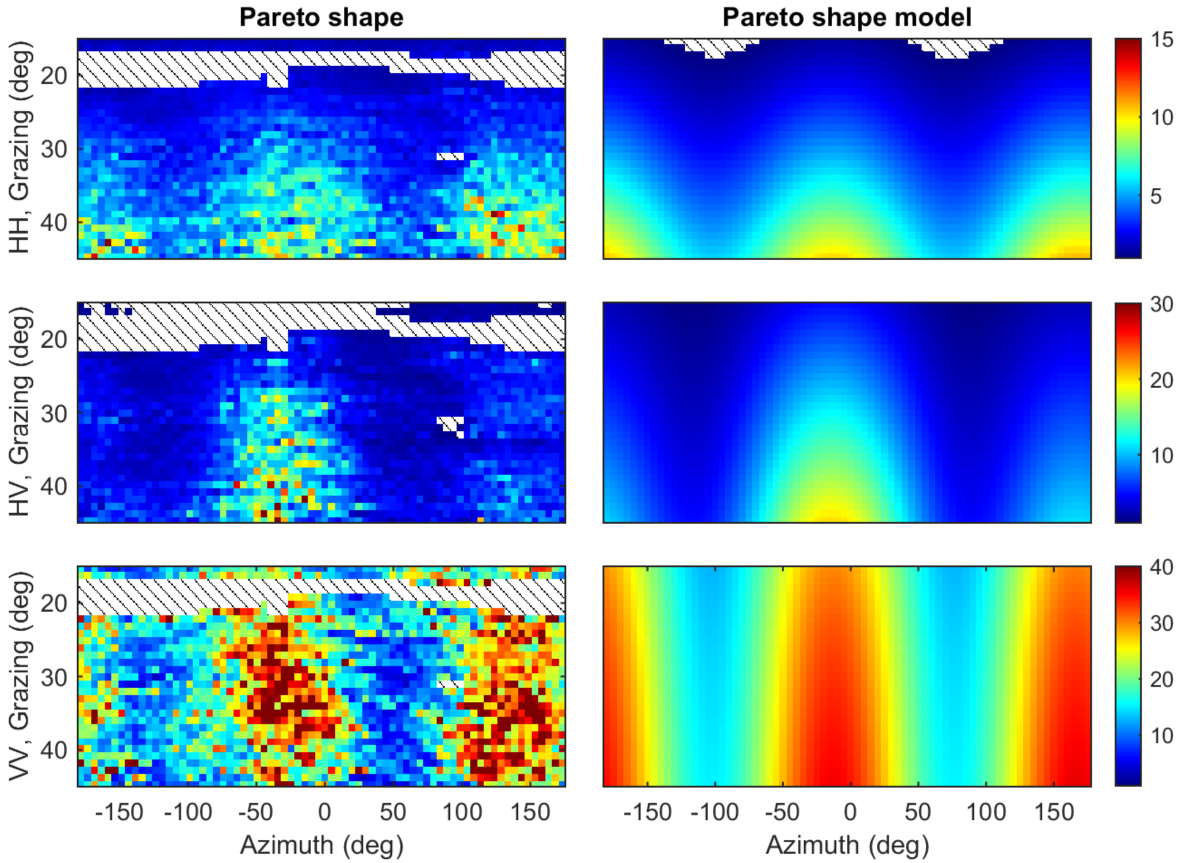
$$\alpha_0 = a_0 \eta_0^{\gamma},\ \alpha_1 = a_0 a_1 \eta_0^{\gamma},\ \ \dots,\ \alpha_4 = a_0 a_4 \eta_0^{\gamma}\ .$$

- The model is then implemented by equating each coefficient $\gamma, \alpha_0, \ldots, \alpha_4$ to the model Y in (2).
- Results in 18 coefficients per polarisation.
- Fixed the normalisation factor to 30°.

- Model is used for the shape, ν, spatial decorrelation length, Doppler spectrum parameters A, B, m_s and σ_s.

Example parameter model

- Results show measured Pareto shape / model.
- Some regions where shape is less than 1 – model is not valid.



Modelling sea-spikes

- To improve sea-spike modelling, use bi-modal spectrum model:

$$G_{\mathrm{bi}}(f,\tau,s,\boldsymbol{\Omega}) = (1-\beta)G_0(f,\tau,s_1,\boldsymbol{\Omega}) + \beta G_0(f,\tau,s_2,\boldsymbol{\Omega})$$

- Gaussian mixture model with ratio β for each component.
- Discrete scatterers due to targets or sea-spikes will cause an extra Doppler spread due to scanning motion of radar:

$$s_{\mathrm{scan}} = \frac{\sqrt{2ln2}}{2\pi}\frac{\omega_{\mathrm{scan}}}{\phi_{\mathrm{3dB}}}$$

where ϕ_{3dB} is the azimuth 3dB beamwidth, ω_{scan} is the scan rate.

- Set Doppler spread, $s_1(\boldsymbol{\Omega}) = s(\boldsymbol{\Omega})$, second spread component:

$$s_2(\boldsymbol{\Omega}) = \sqrt{s^2(\boldsymbol{\Omega}) + s_{\mathrm{scan}}^2}$$

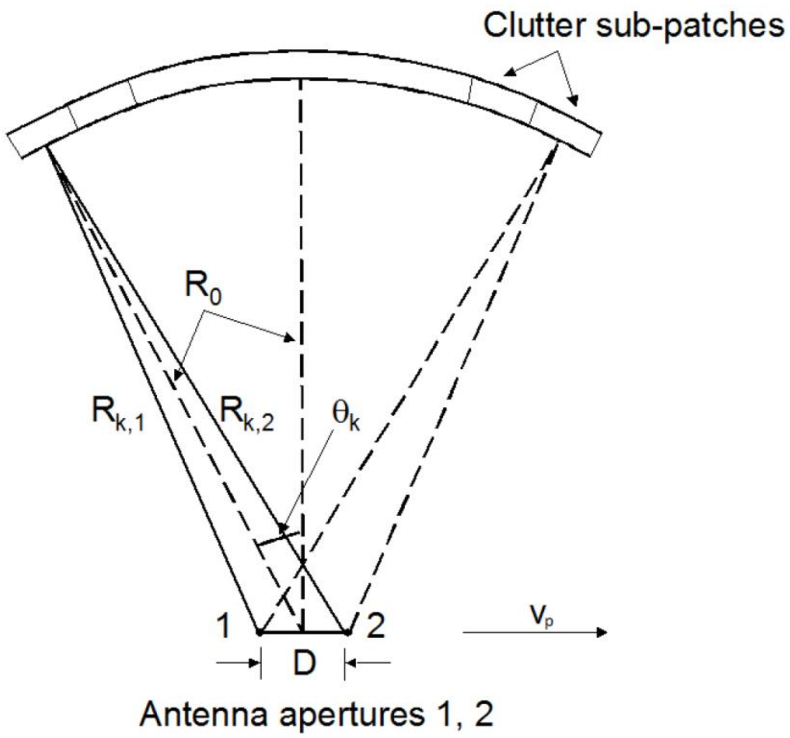
Multiple phase centres

- Require representation of K clutter sub-patches where *D* is the spacing between phase centres.
- See example for 2 apertures:
- Texture is broken up into K parts:

$$\sum_{k=1}^{K} \tau_k = \tau$$

where $\tau_k = A(f_k)\tau$ models the return from each part of the beam.

- Can now remove beampattern convolution – i.e just use G_0 or G_{bi}.



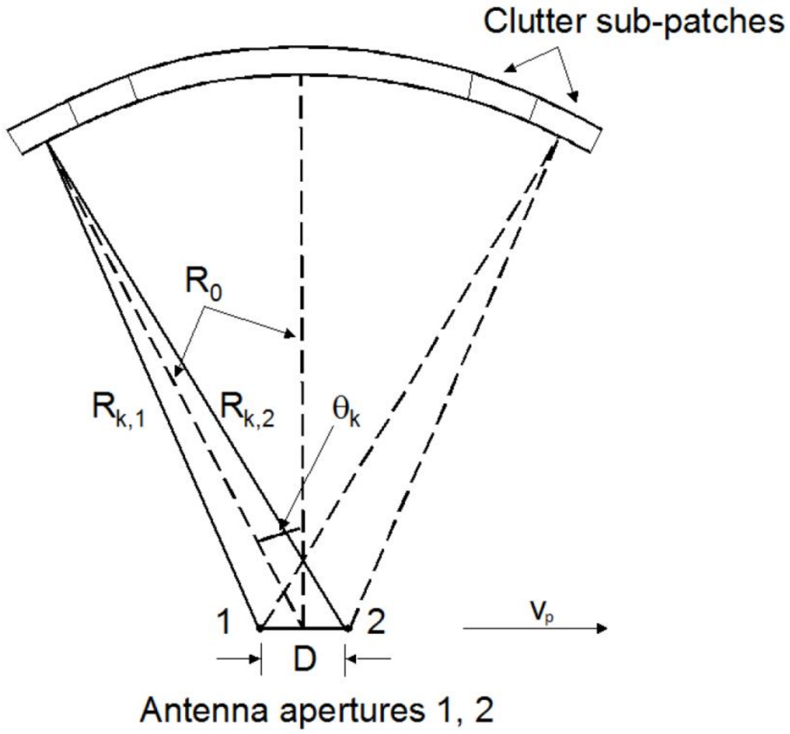
Multiple phase centres

- Need to adjust platform Doppler shift: $f_{\text{plat}} = {}^{2v_p}/_{\lambda} \cos(\theta_{\text{plat}} - \theta_k)$.
- Overall return from l^{th} sub-aperture:

$$\tilde{y}_l(m) = \sum_{k=1}^{K} y(m, \tau_k) \exp\left(\frac{j2\pi}{\lambda}(R_{k,l} - R_{k,1})\right)$$

$$\approx \sum_{k=1}^{K} y(m, \tau_k) \exp\left(\frac{j2\pi}{\lambda} D(l-1)\sin\theta_k\right)$$

- Implementation more computationally intensive due to extra summation.
- Can reduce this by only including those sub-patches where $A(f_k) > \epsilon$, where $\epsilon \approx 10^{-3}$.



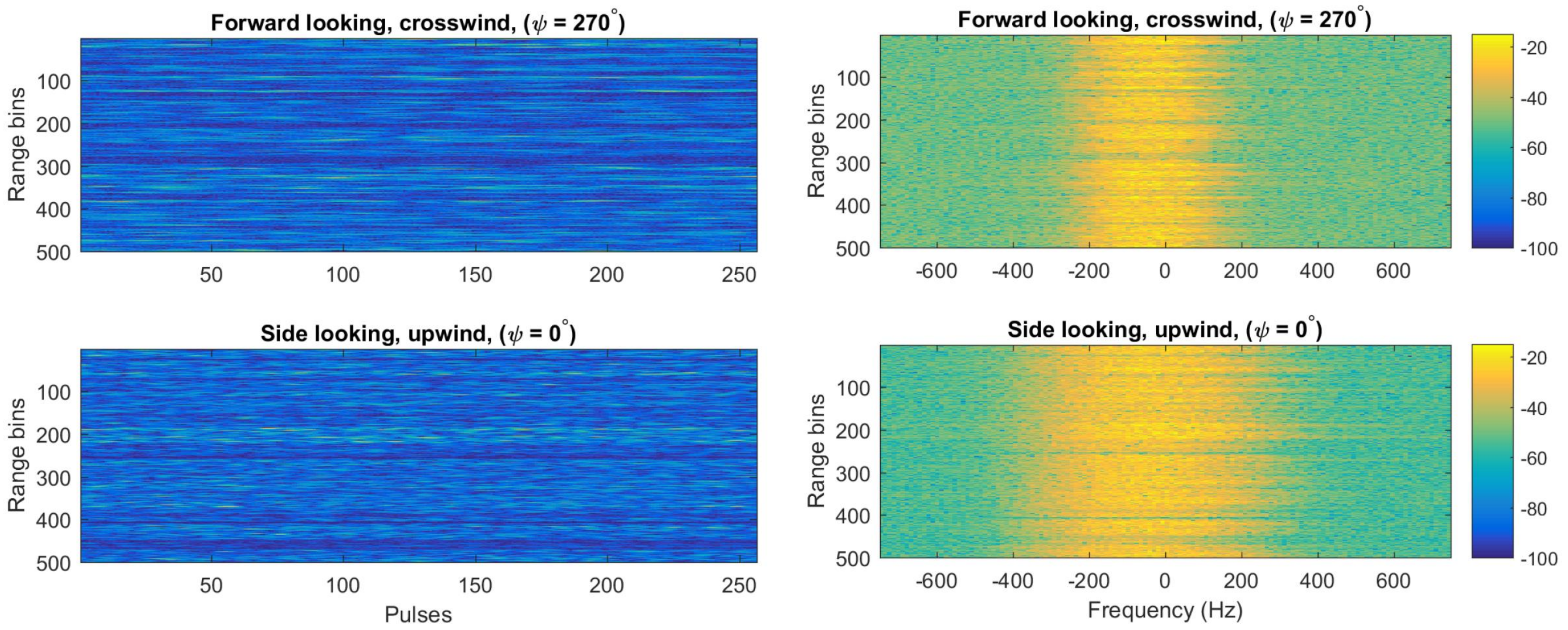
Simulation examples

- Consider the following example with the radar scanning clockwise with the radar platform heading North.
- Wind and swell are both coming from the West.
- Filter order N=64.

Radar scan rate	5 rpm
Aircraft speed	80 m/s
Azimuth 3 dB beamwidth (two-way)	3°
Centre frequency	10 GHz
Bandwidth	200 MHz
Pulse repetition frequency	3 KHz
Grazing angle	30°
Sea state	3
No. of pulses a target will be in the beam	300
Amplitude PDF model	K distribution
Spectral model	Bimodal

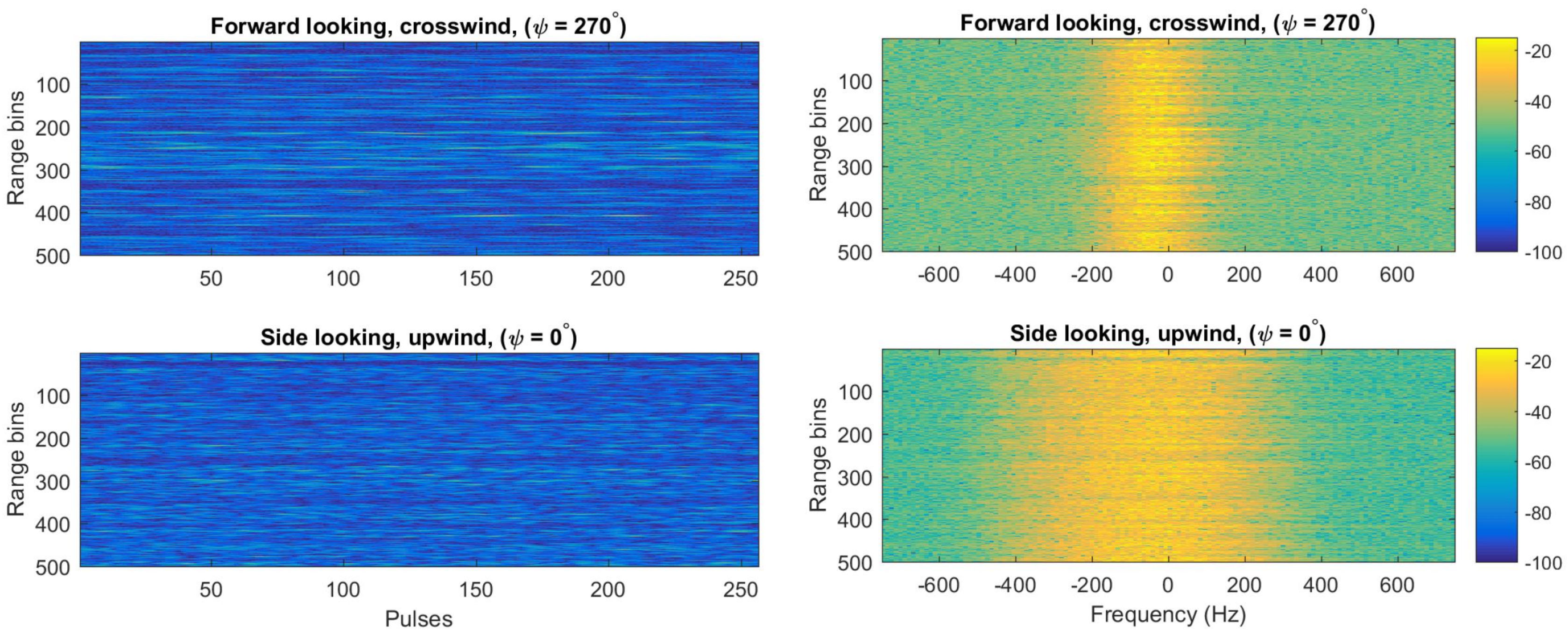
Single aperture results

- Range / time result shown on left for the forward looking (crosswind) and side looking (upwind) cases.
- Doppler spectrum shown on right (after Doppler centroid correction) with greater correlation in the forward looking case (narrower spectrum).



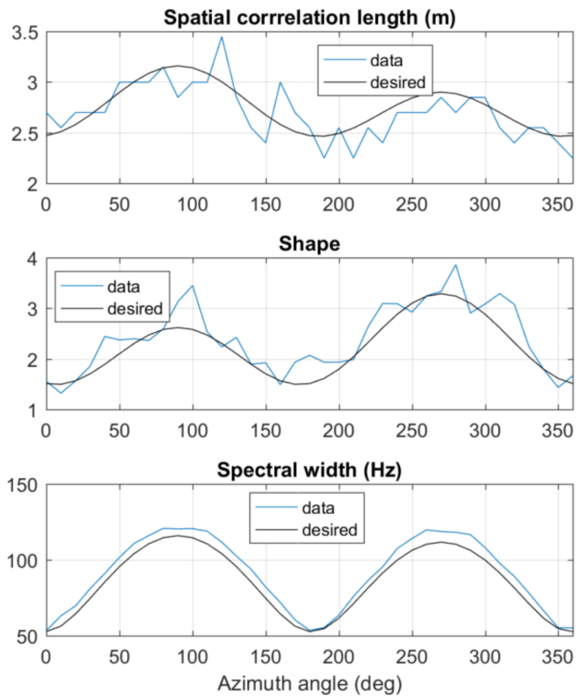
Multi-aperture results

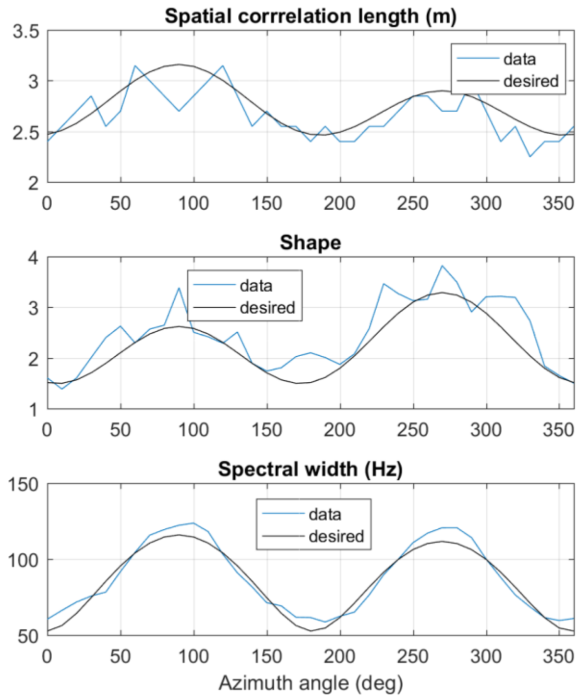
- Multi-aperture model has $D = \frac{\lambda}{2}$ and $L = 10$ spatial channels.
- Forward looking spectrum appears narrower, but on average (over range) the width is correct.



Simulation verification

- Simulation is verified by comparing the estimated spatial correlation, shape and spectral width with the desired / specified values around the orbit.
- All estimated results show a close match with the desired ones.
- Left - single aperture, right – multi-aperture.





Multi-aperture power spectra

- Fourier / optimum power spectrum used to verify the multi-aperture simulation.

$$P_F = \boldsymbol{v}^H(\theta, f)\widehat{\boldsymbol{R}}\boldsymbol{v}(\theta, f)$$

$$P_{\text{opt}} = \frac{1}{\boldsymbol{v}^H(\theta, f)\widehat{\boldsymbol{R}}^{-1}\boldsymbol{v}(\theta, f)}$$

with steering vectors:

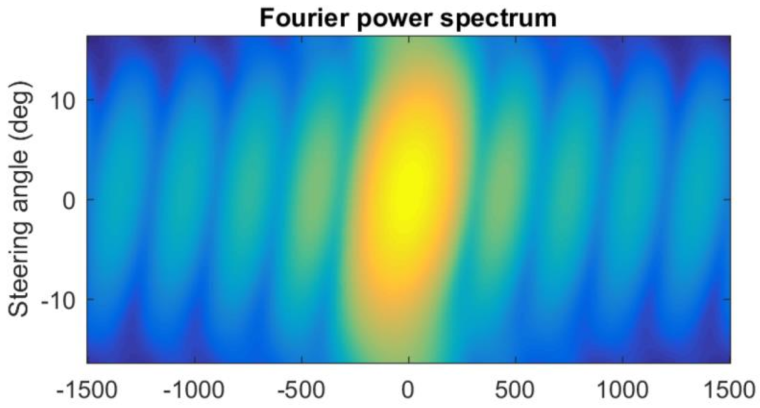
$$\boldsymbol{v}(\theta, f) = \boldsymbol{v}_{\text{spat}}(\theta) \otimes \boldsymbol{v}_{\text{temp}}(f) \in C^{LC\times 1}$$

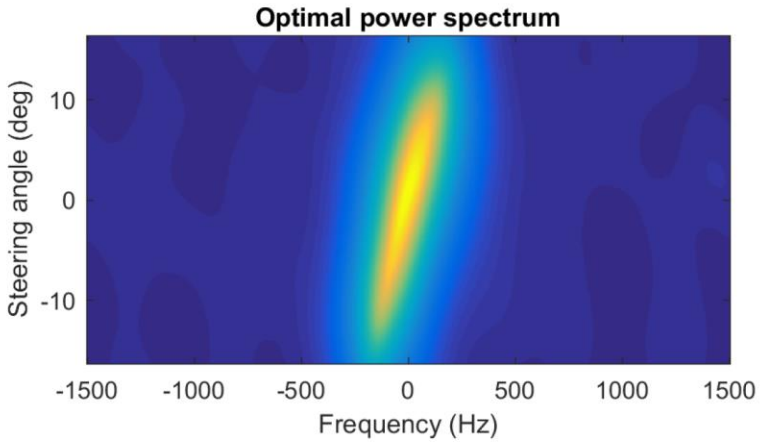
containing elements:

$$v_{\text{spat,l}}(\theta) = \exp\left[j2\pi(l-1)\frac{d}{\lambda}\sin(\theta)\right]$$

$$v_{\text{temp},c}(f) = \exp\left[j2\pi(c-1)\frac{f}{f_r}\right]$$

Covariance estimated with sample covariance matrix: $\widehat{\boldsymbol{R}} = \sum_{q=1}^{2LC} \boldsymbol{y}_q \boldsymbol{y}_q^H$.





Conclusions and future work

- Sea clutter simulation method presented for both single and multi-aperture scanning radars.
- Simulation verified by comparing the estimated shape, spatial decorrelation length and spectral widths with the desired values.
- Multi-aperture simulation also verified by forming the Fourier and optimal spectra.
- Future work will investigate the extension of the parameter models to include:
  - variation of the CNR with range,
  - the impact of varying the coherent processing interval when characterising the model parameters,
  - how to include other range resolutions (beyond 0.75 m).