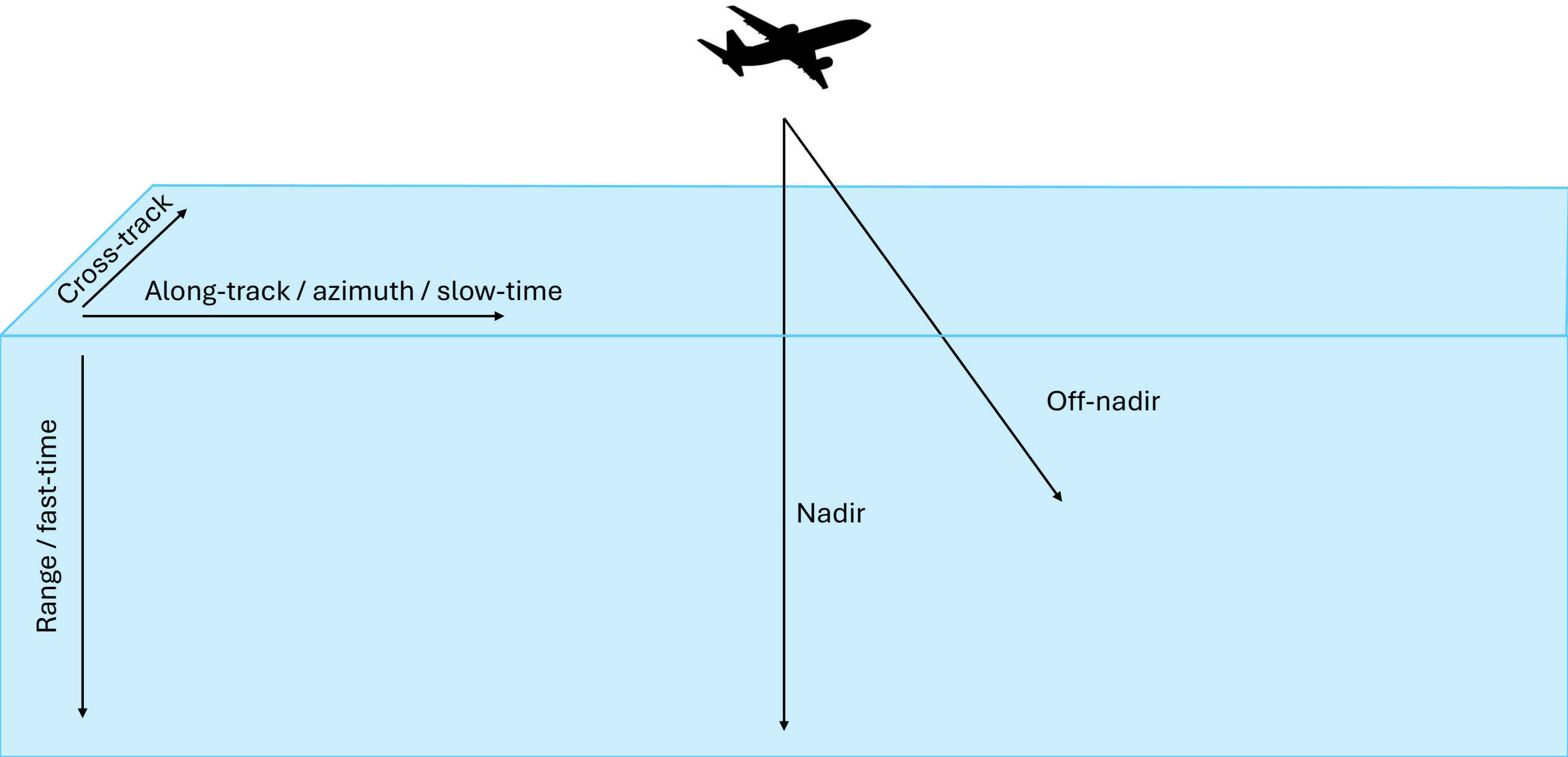
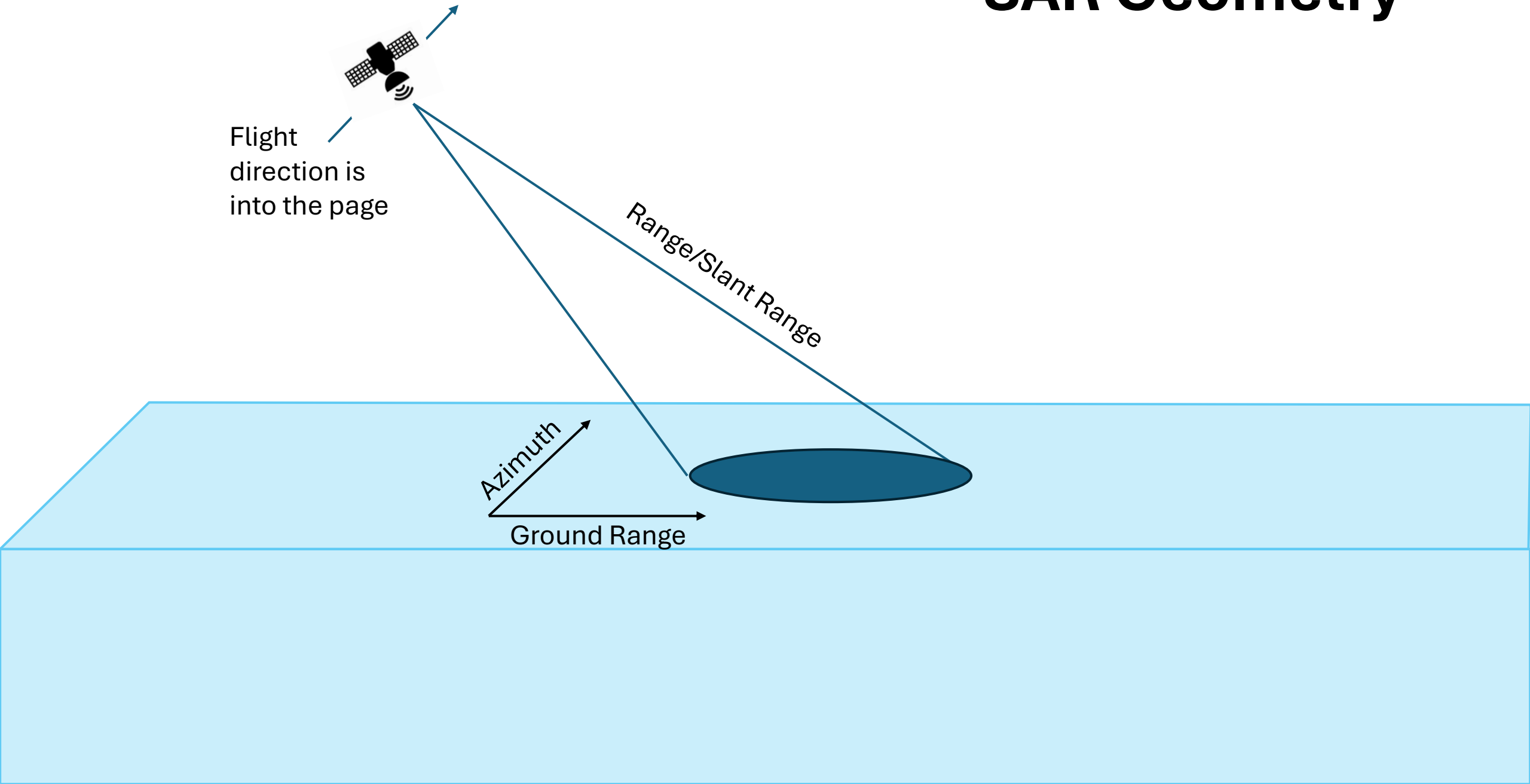
Radar Sounding Geometry



SAR Geometry



Radargrams

What a radar measures:

- Amplitude and phase of the electromagnetic wave as a function of time

What we usually interpret in radargrams:

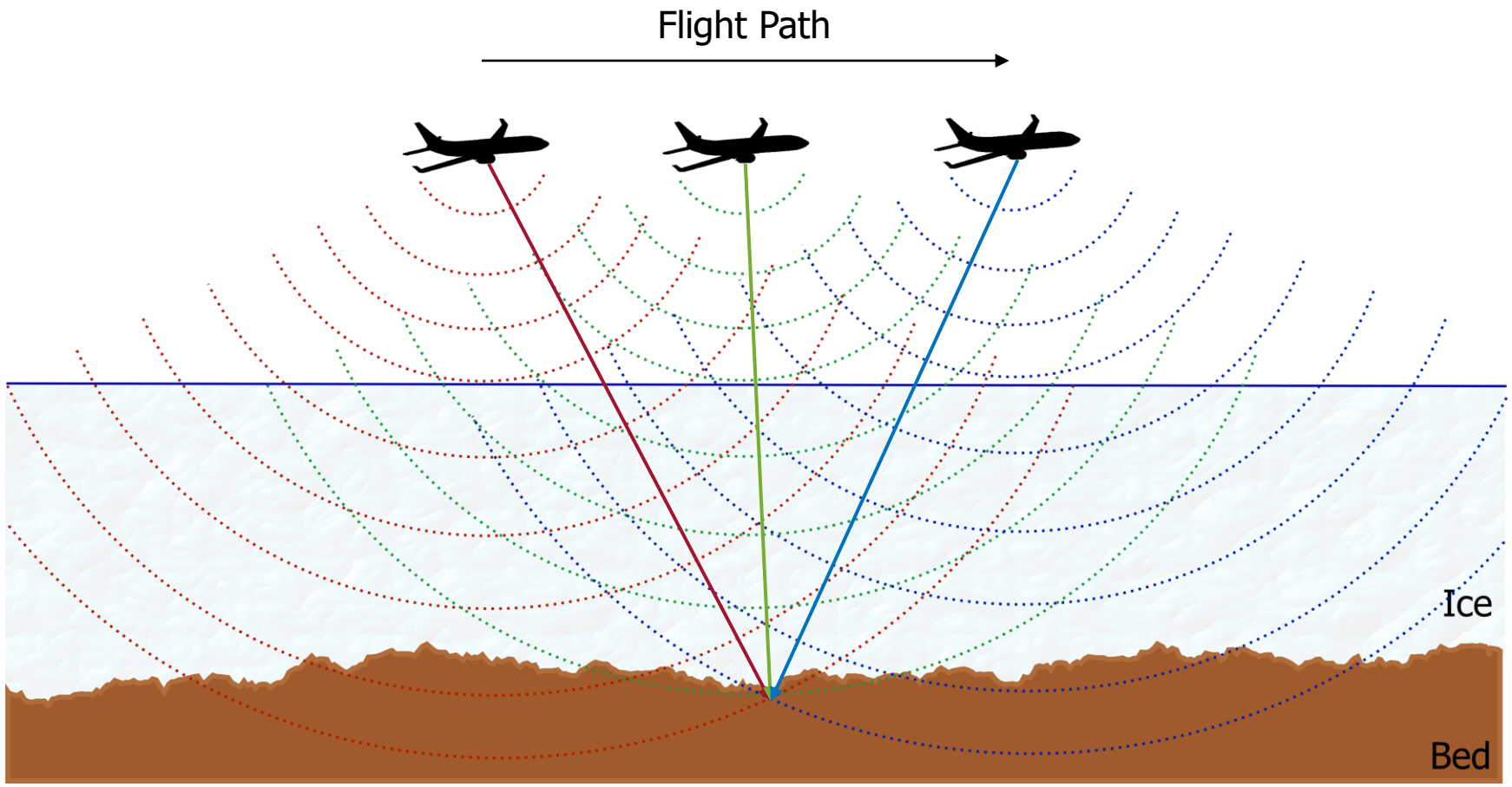
- Power as a function of time

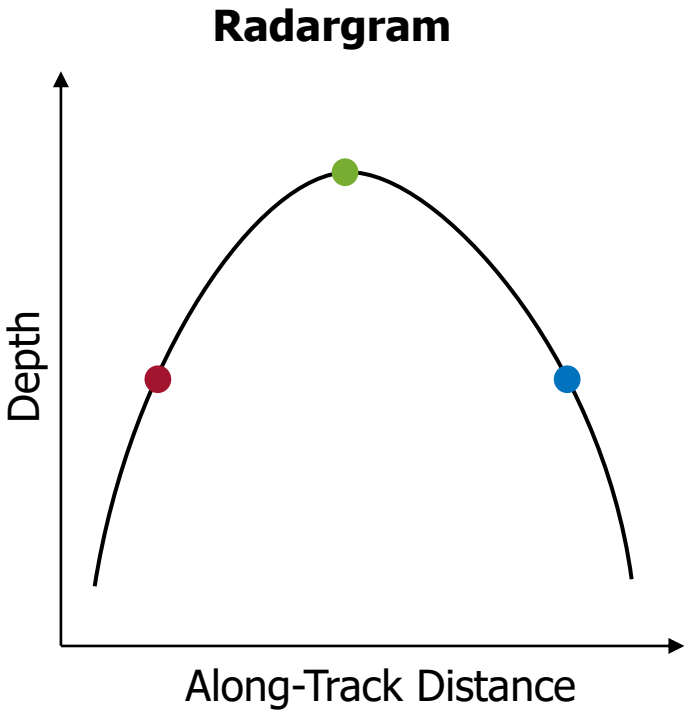
Time to Distance Conversion:

$$d = \frac{0.5ct}{n}$$

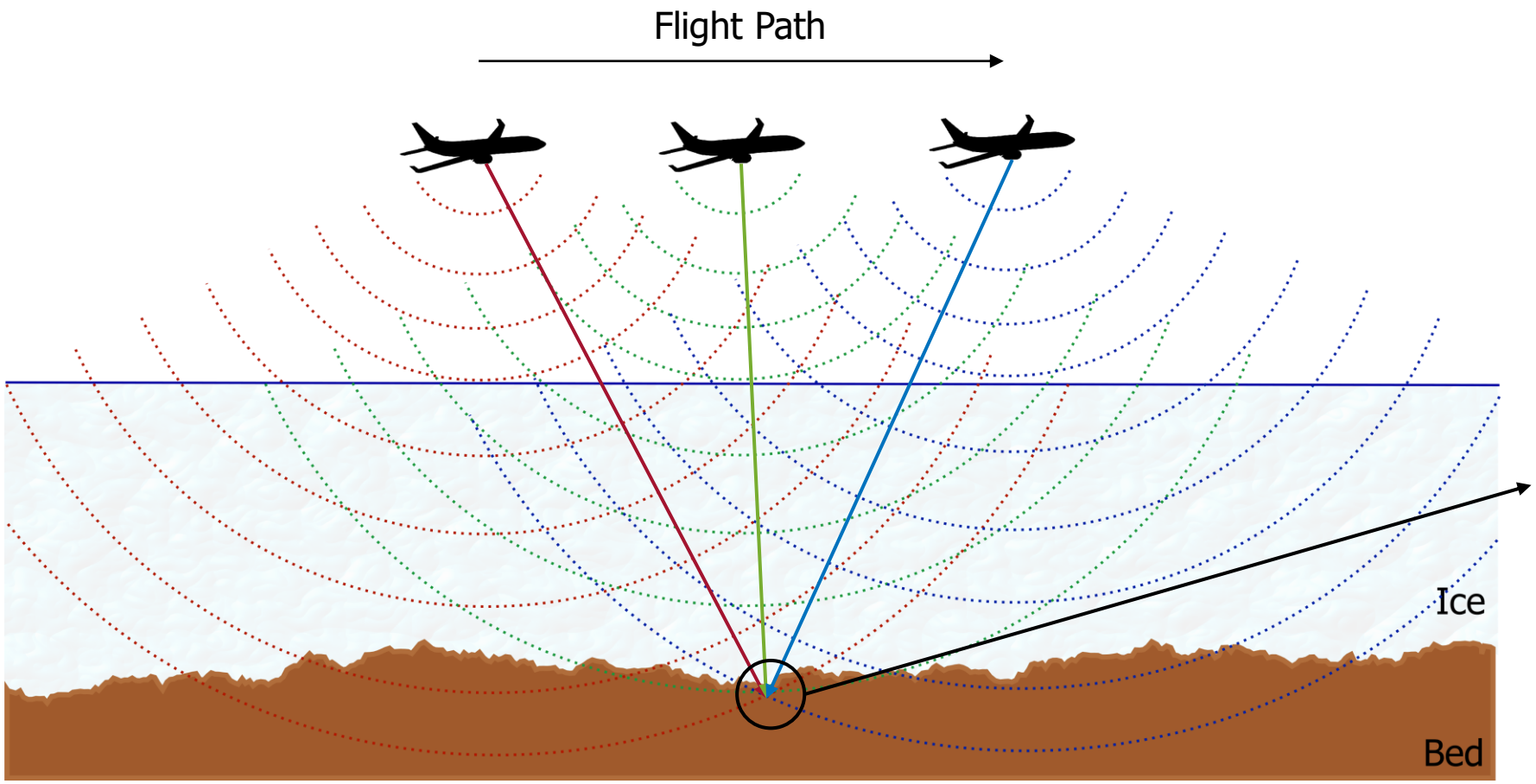
$c =$ speed of light in a vacuum
$t =$ two-way travel time measured by radar
$n =$ refractive index of medium radar is sounding through

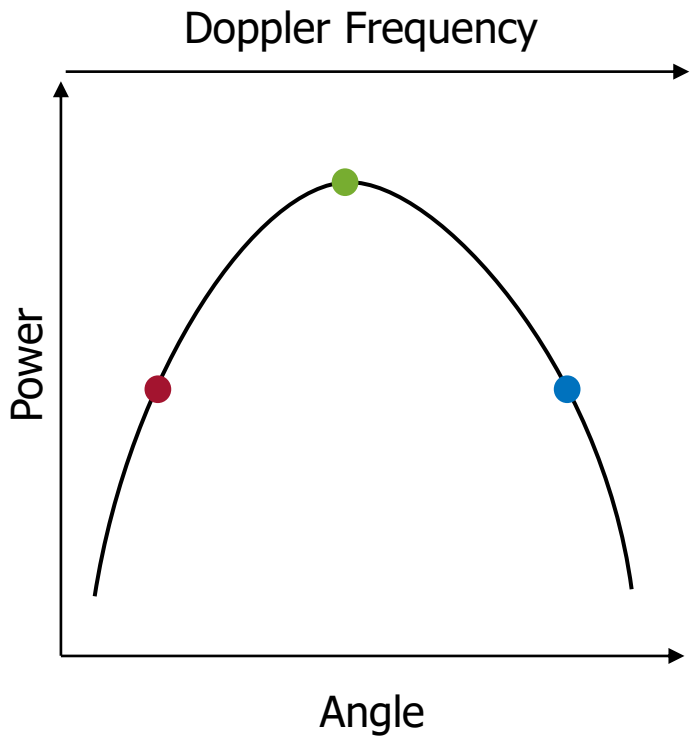
Sounding Geometry for Scattering Targets





Doppler Frequency

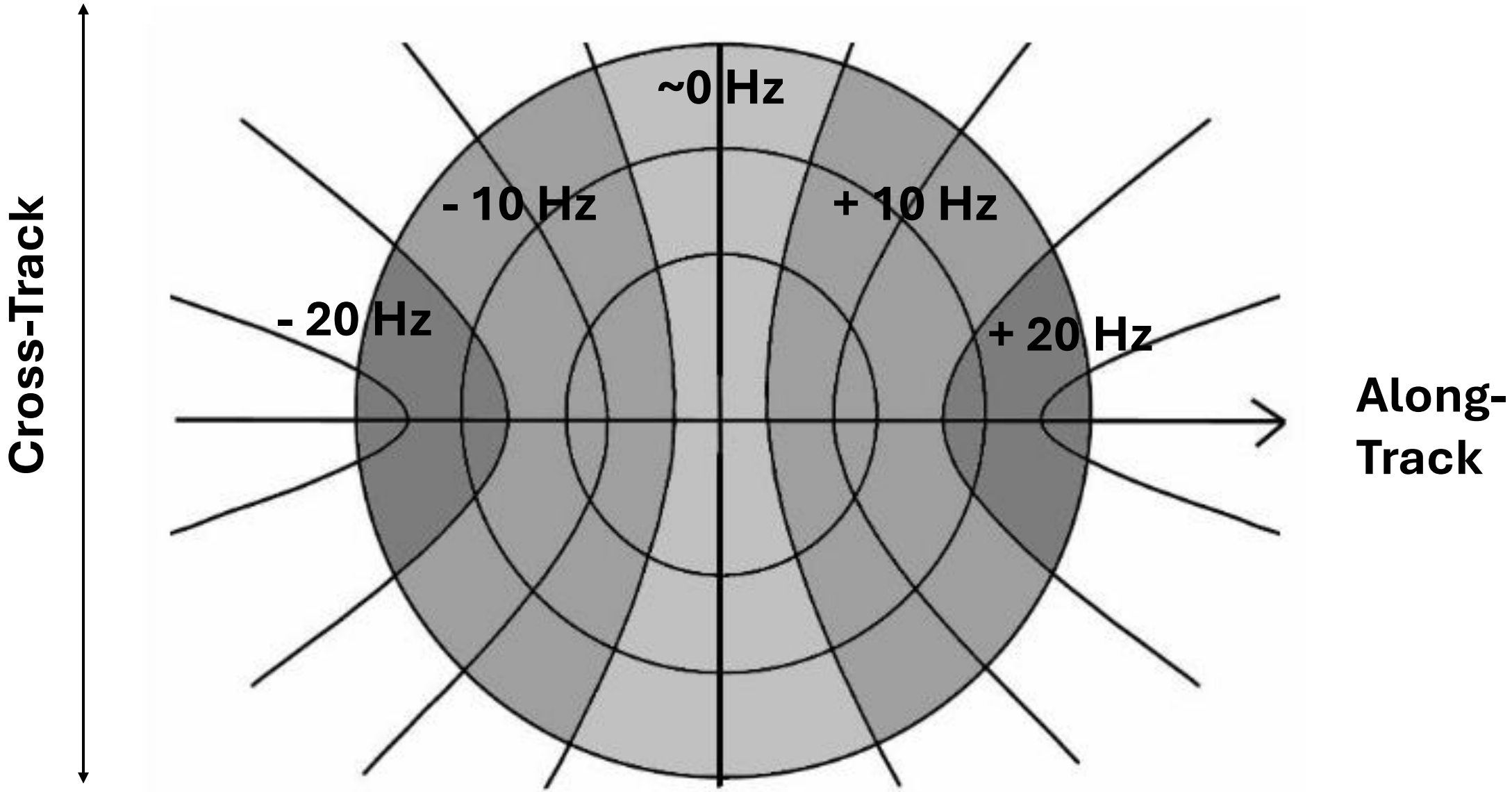




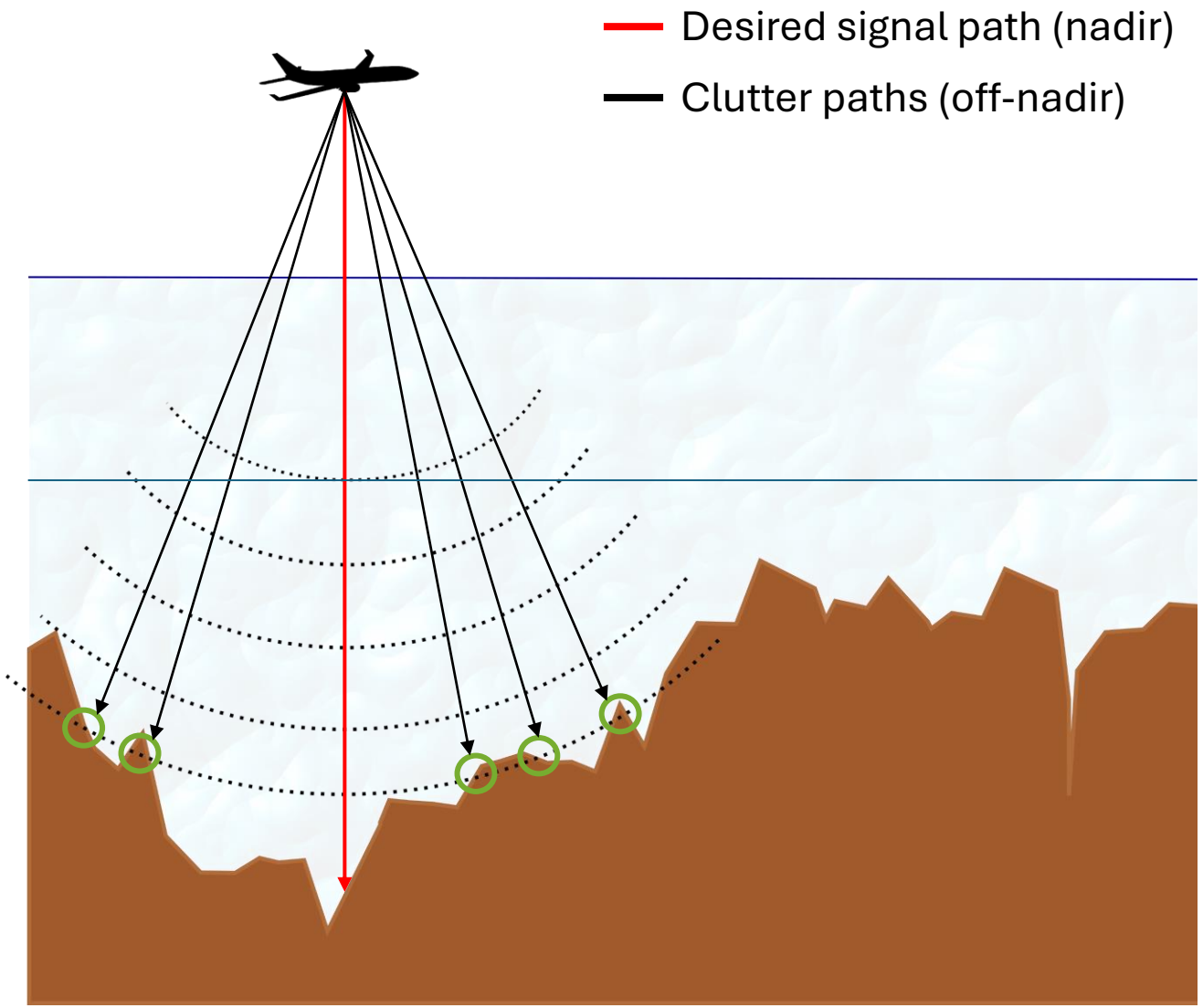
$$f_d = \frac{2v \sin\theta}{\lambda}$$

$v =$ aircraft velocity relative to target
$\theta =$ angle between aircraft and target
$\lambda =$ radar wavelength

Doppler Frequency

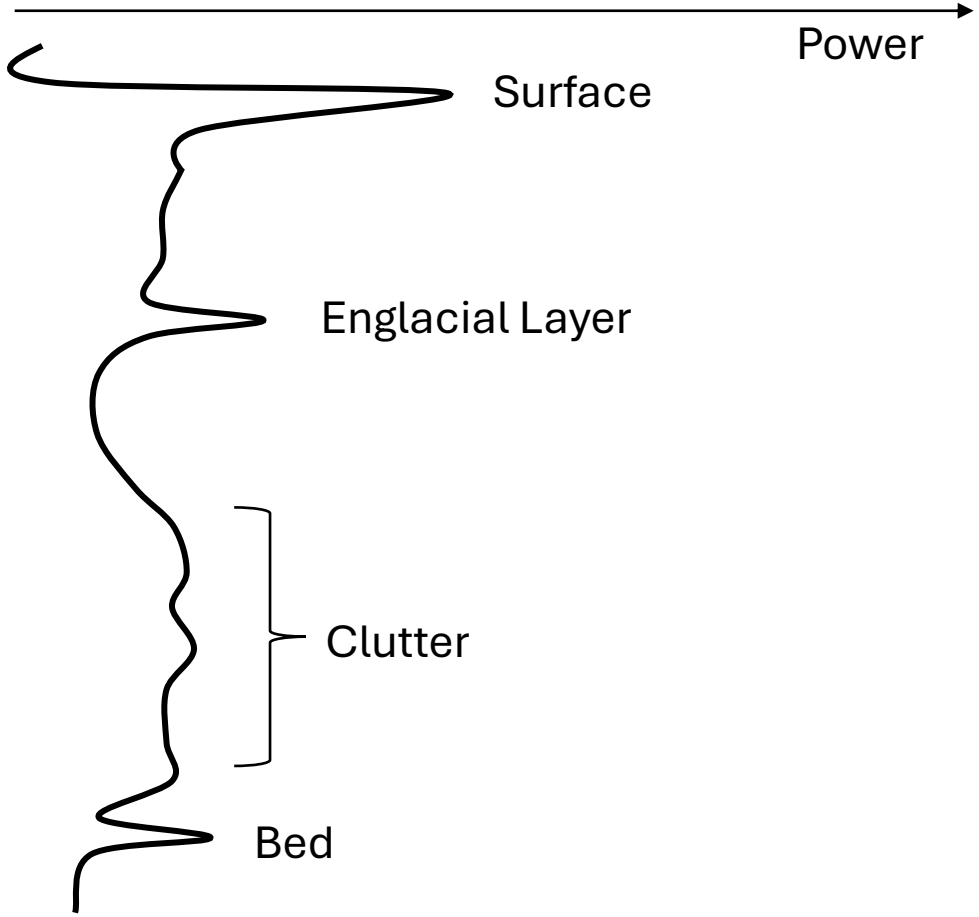


Sounding Geometry and Clutter

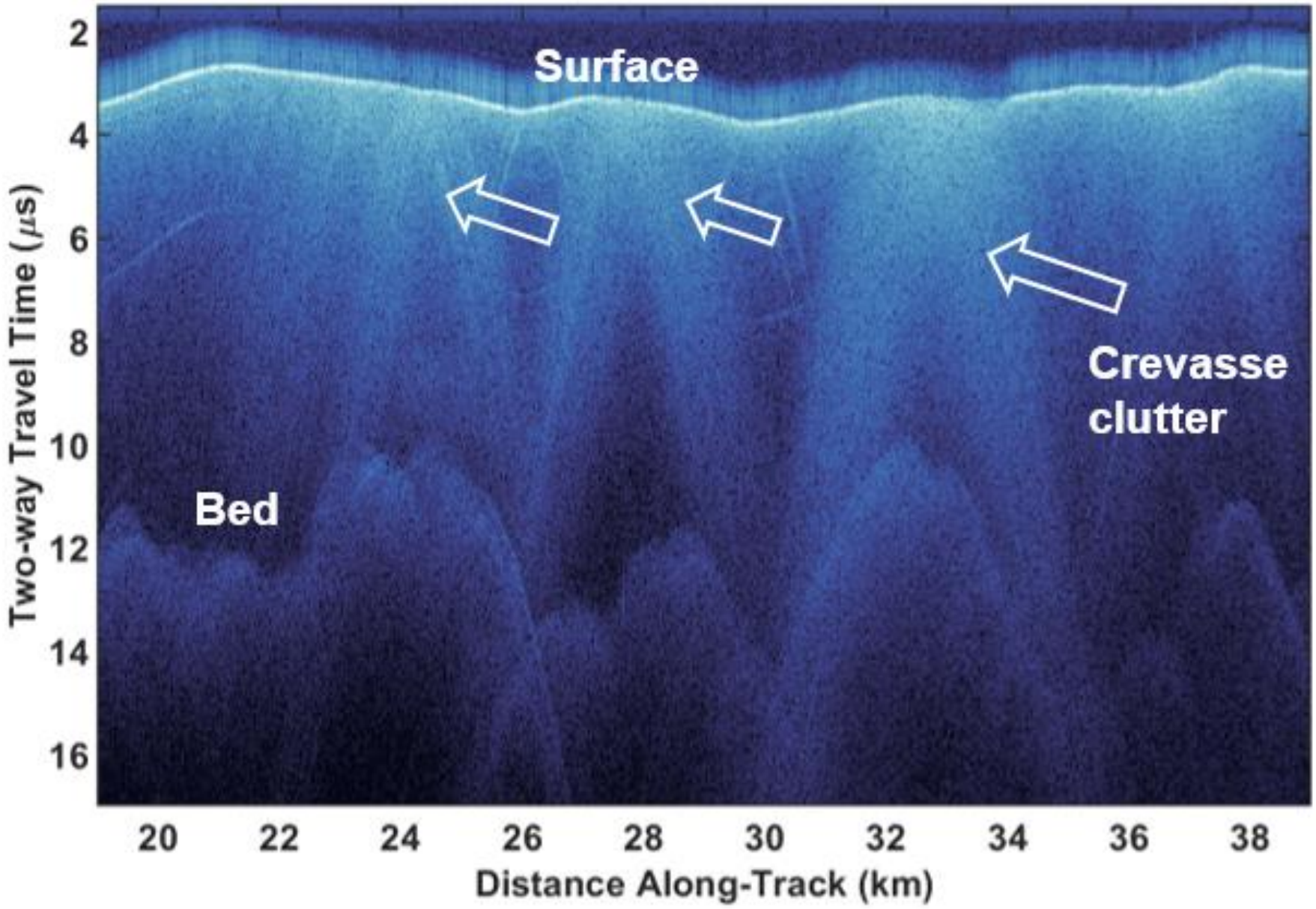


Clutter:

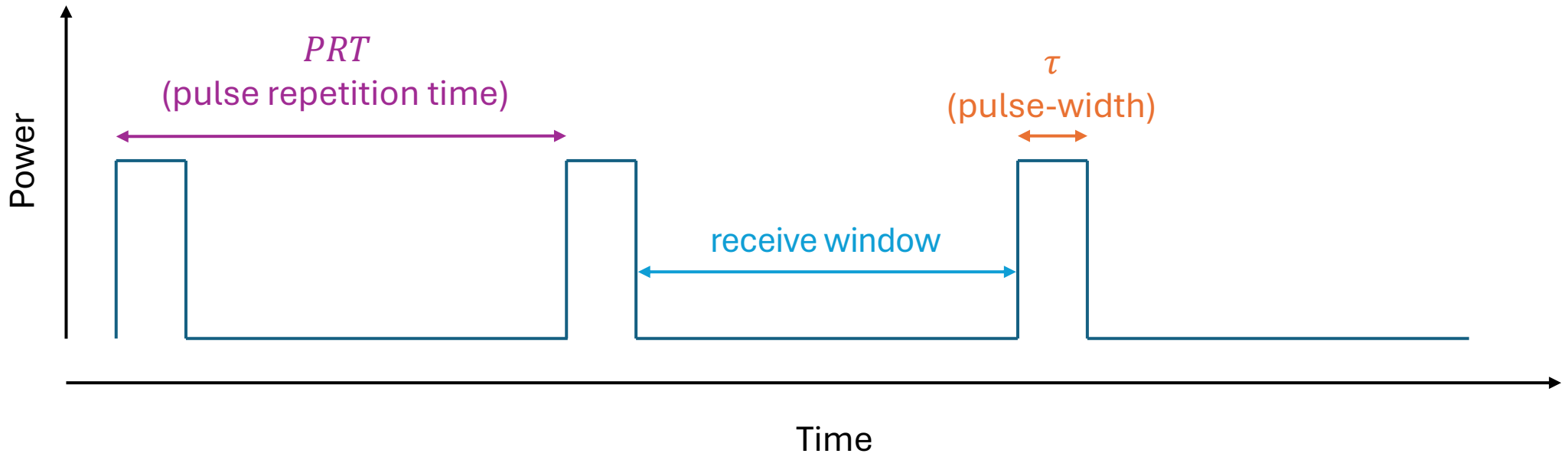
Off-nadir scattered signals that arrive at the radar with the same time delay as the nadir signal of interest.



Scattering and Clutter in Real Data



Pulse Transmission Schemes



PRF = pulse repetition frequency = number of pulses per second

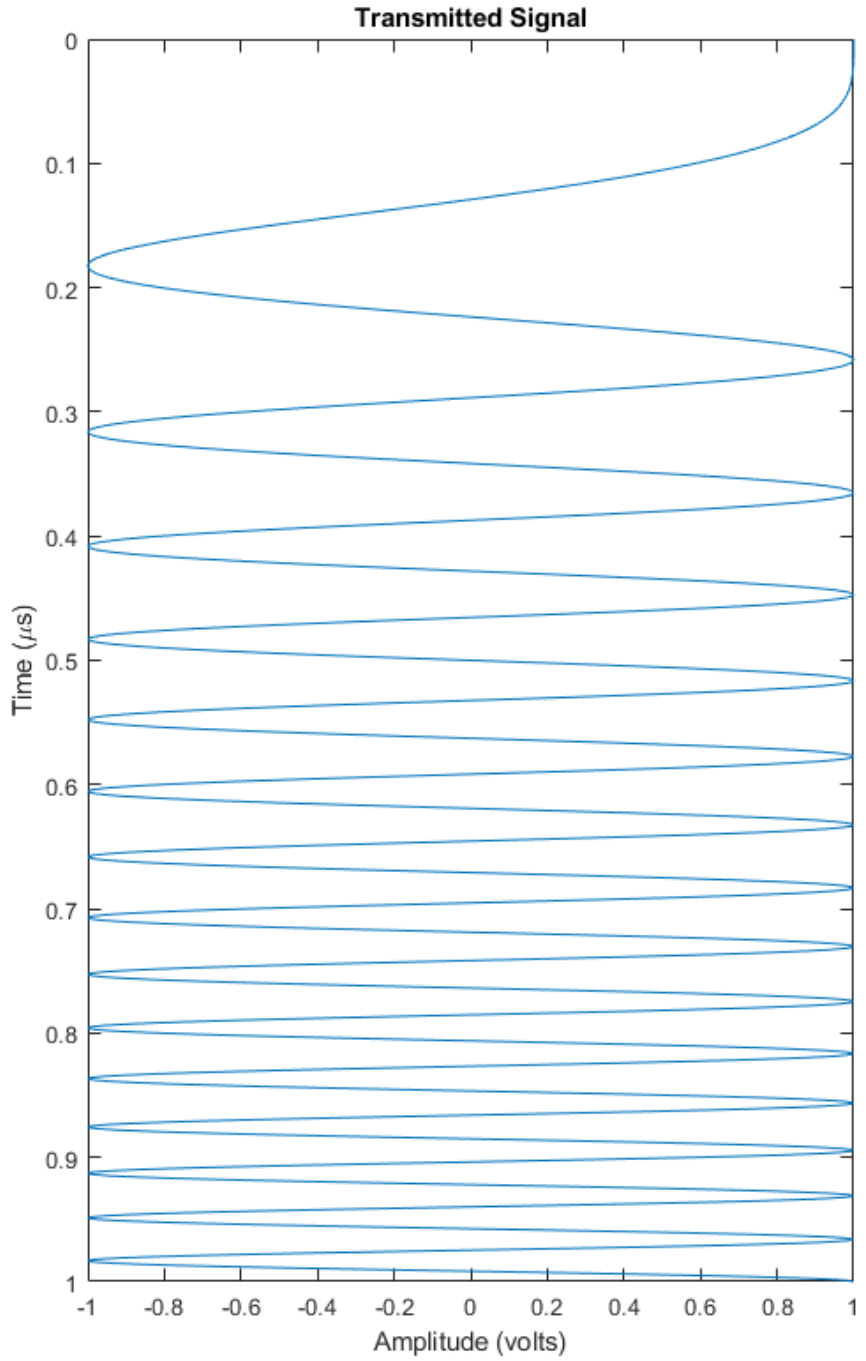
Trace spacing:

$$\Delta x \approx v(PRT) = \frac{v}{PRF}$$

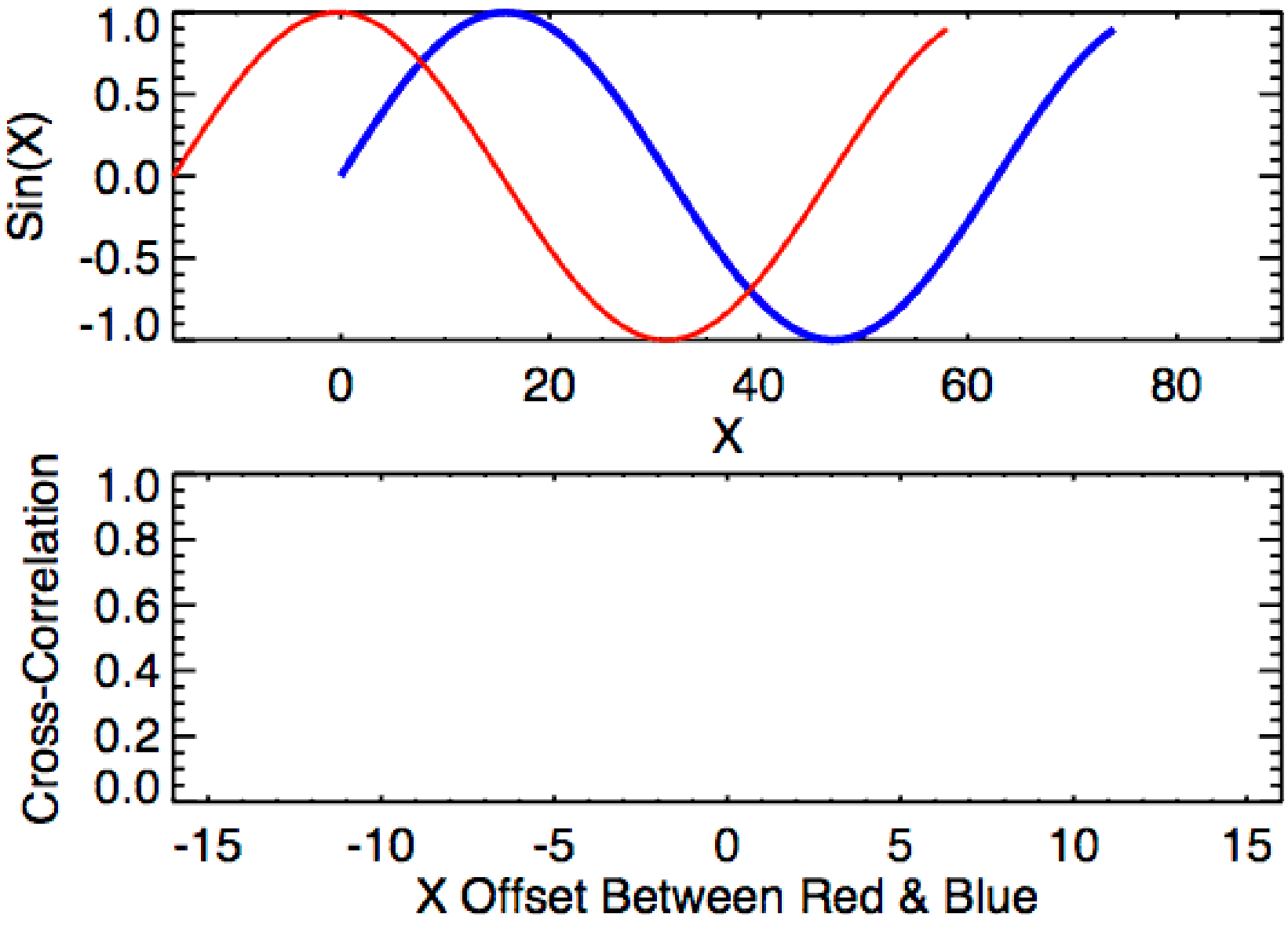
Linear Frequency Modulated (LFM) Waveform

$$s(t) = \mathcal{R}\{A \exp[j(\pi k t^2 + 2\pi f_c t + \phi)]\}$$

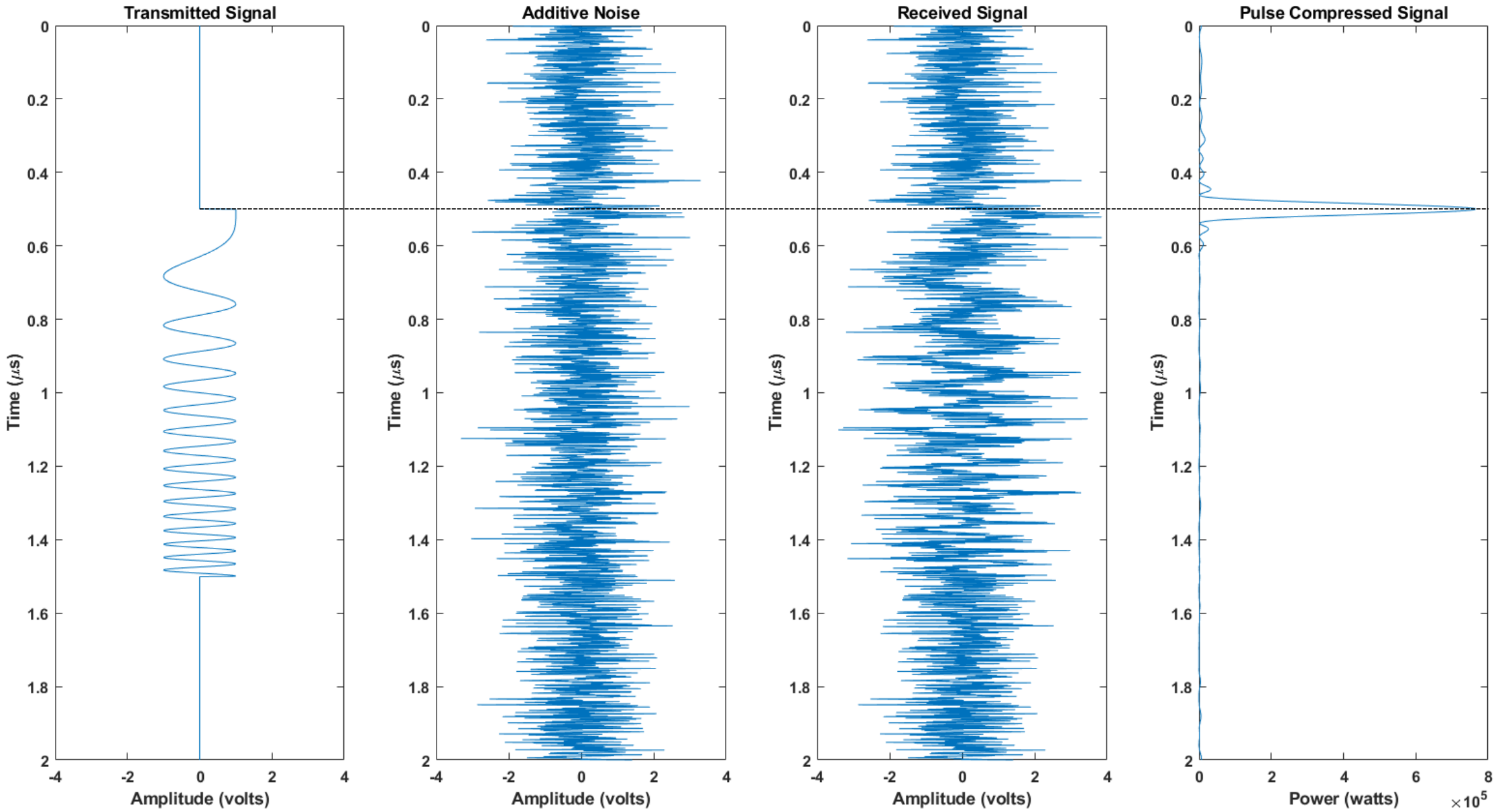
$k = \frac{B}{\tau}$ = rate of frequency increase
B = radar bandwidth (Hz)
τ = pulse-width (s)
f_c = center frequency (Hz)
ϕ = phase (radians)
t = time (s)
V_{max} = maximum voltage
$s(t)$ = signal amplitude as a function of time



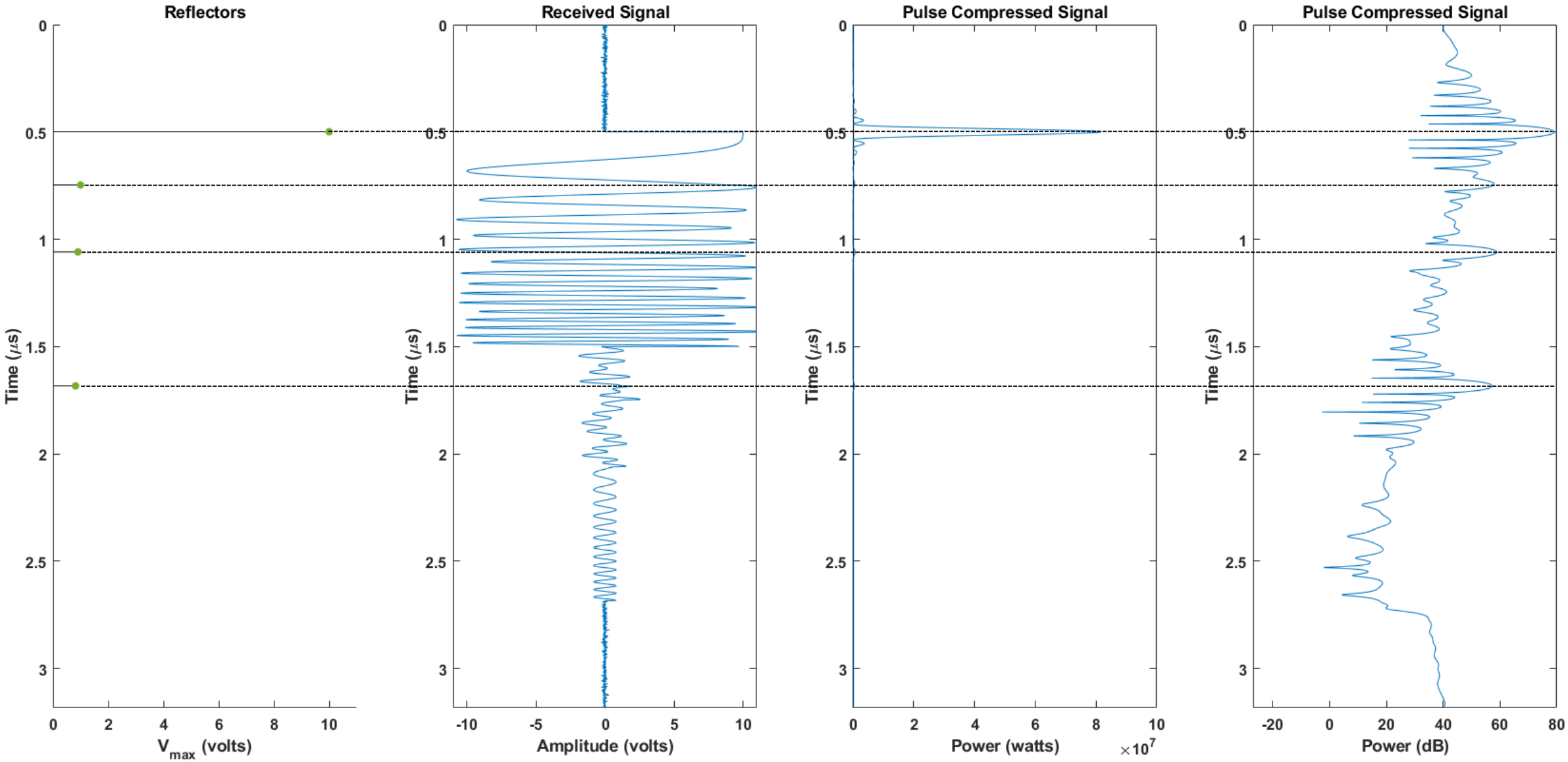
Convolution



Range Compression - Improving SNR



Range Compression – Improving Resolution



Improving SNR & Resolution

$$\boldsymbol{SNR\ gain = B\tau w_p}$$

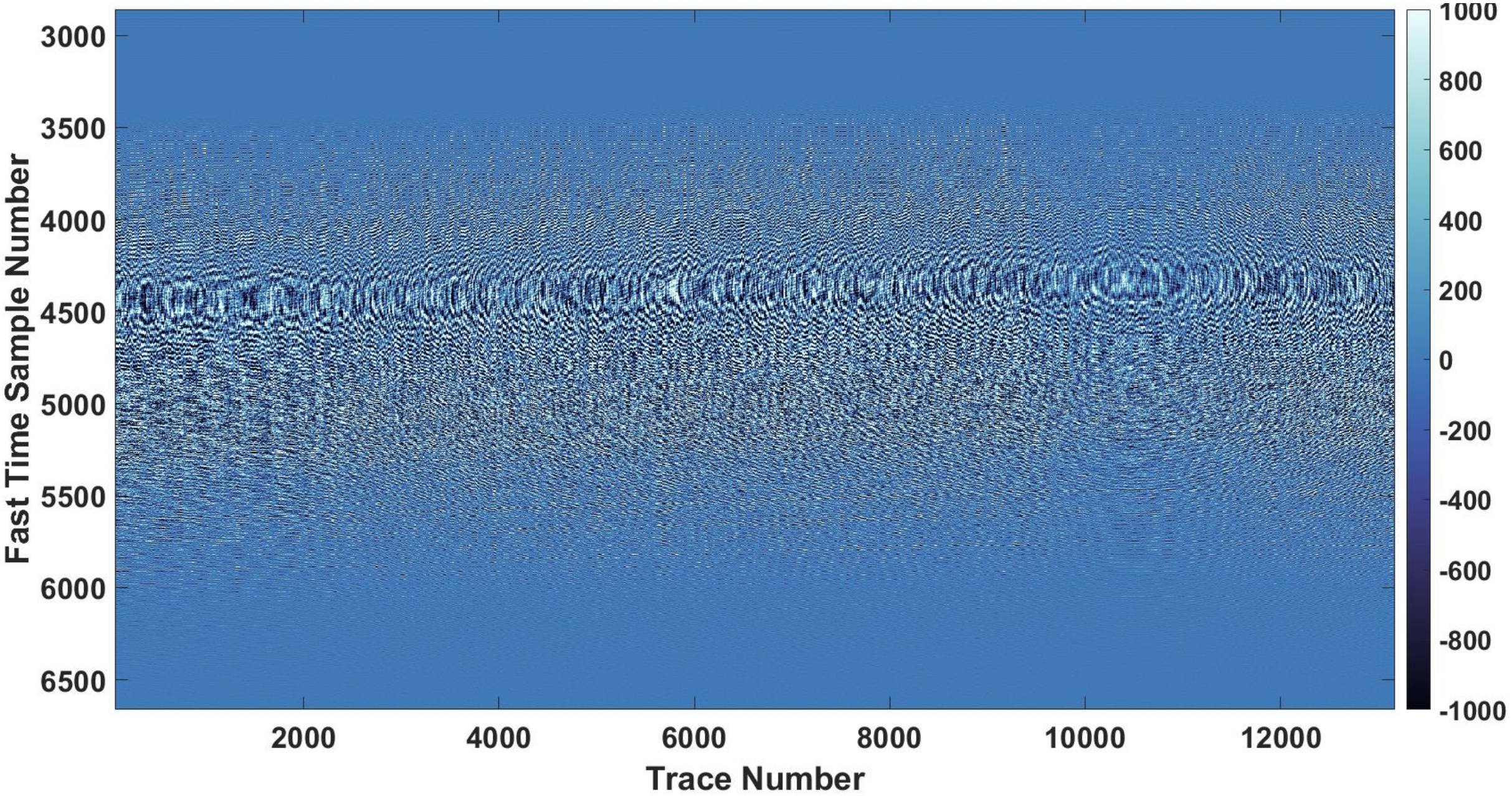
(time-bandwidth product)

B = radar bandwidth (Hz)
τ = pulse-width
w_p = windowing factor

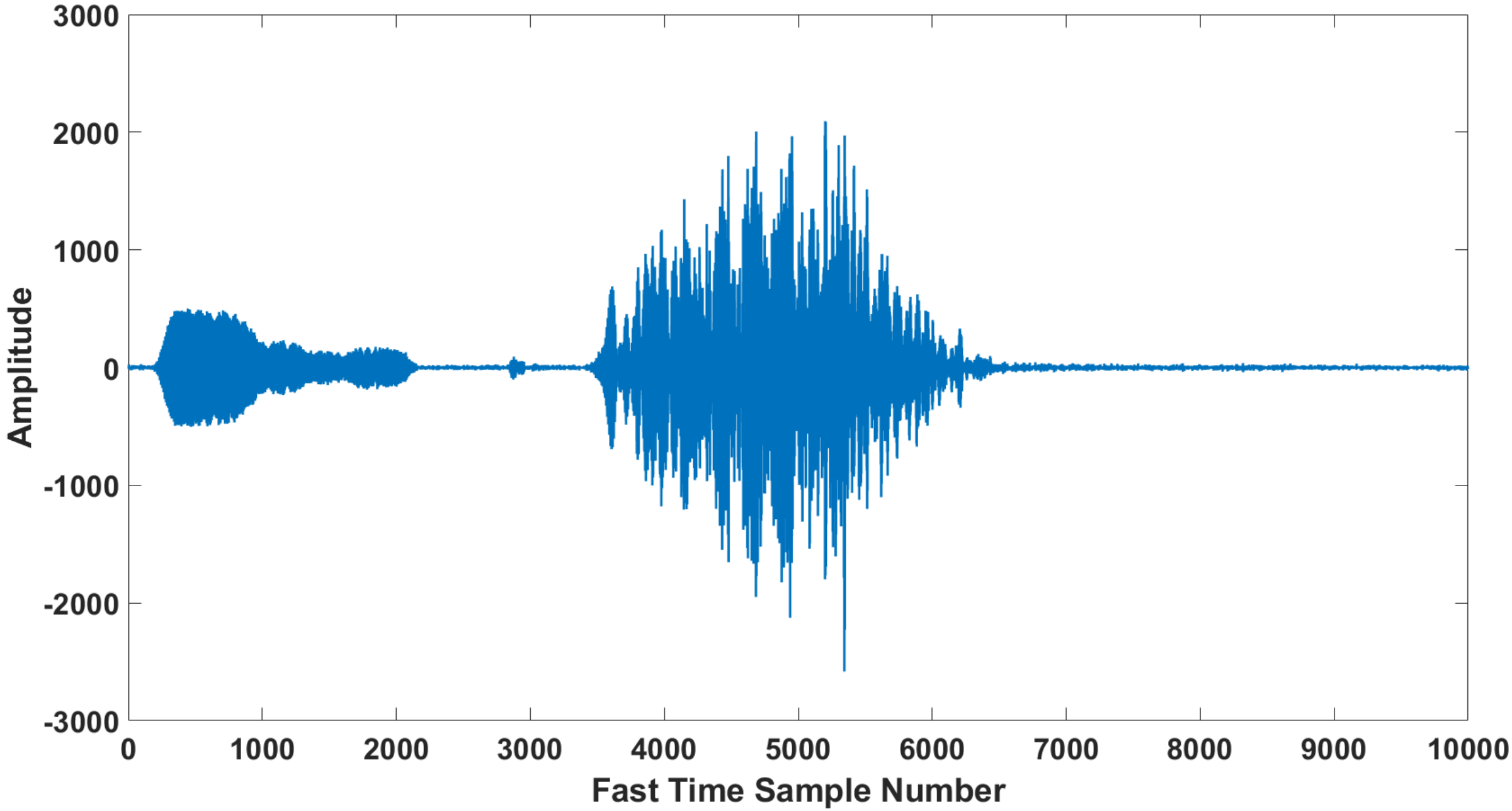
$$\boldsymbol{\Delta r = \frac{c w_t}{2B}\ (\text{in air})} \qquad \boldsymbol{\Delta r = \frac{c w_t}{2nB}\ (\text{in ice})}$$

c = speed of light in vacuum (299,792,458 m/s)
B = radar bandwidth (Hz)
w_t = windowing factor
n = refractive index of ice (or firn or snow, etc)

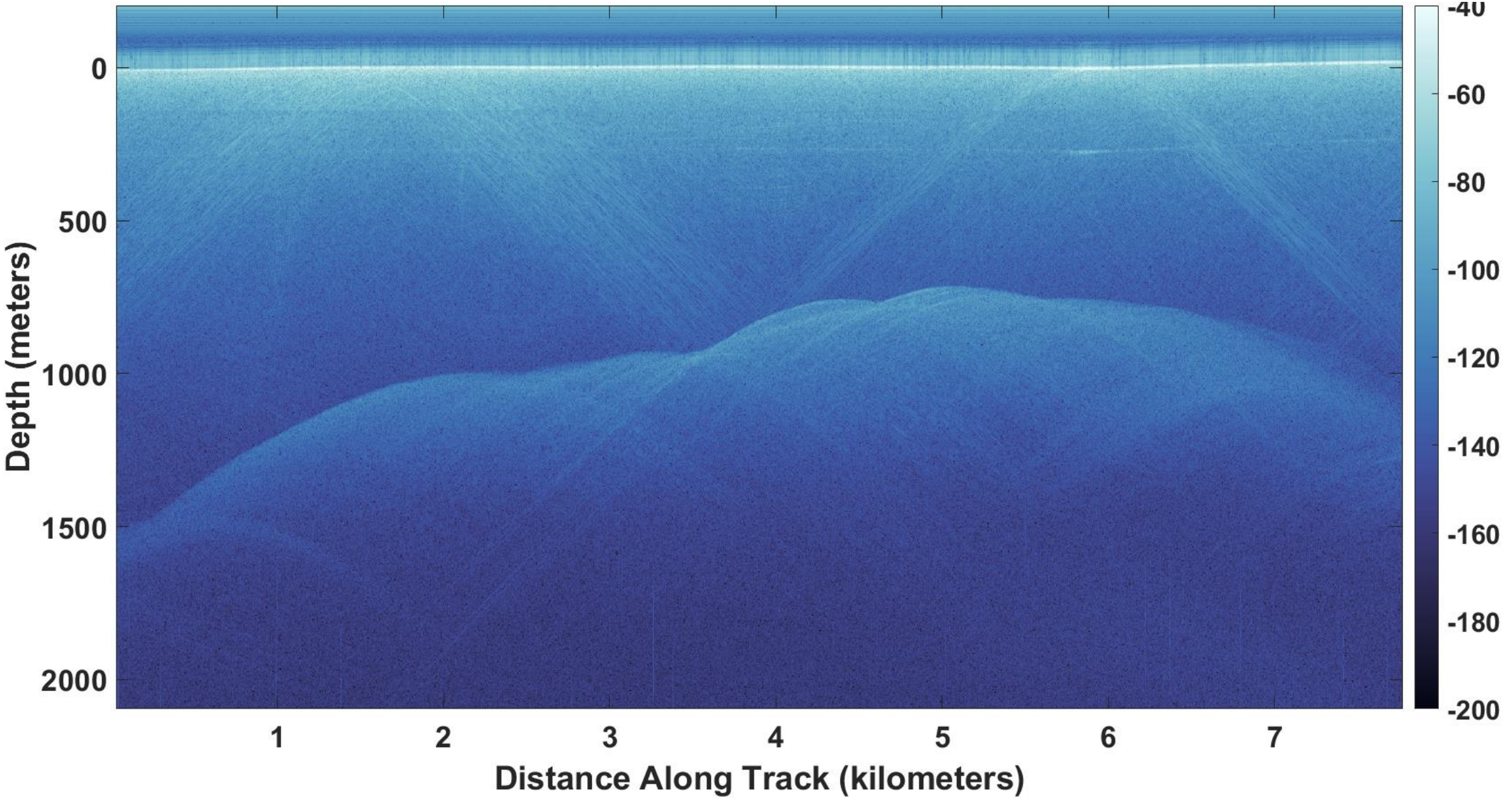
Range Compression – Raw Radargram



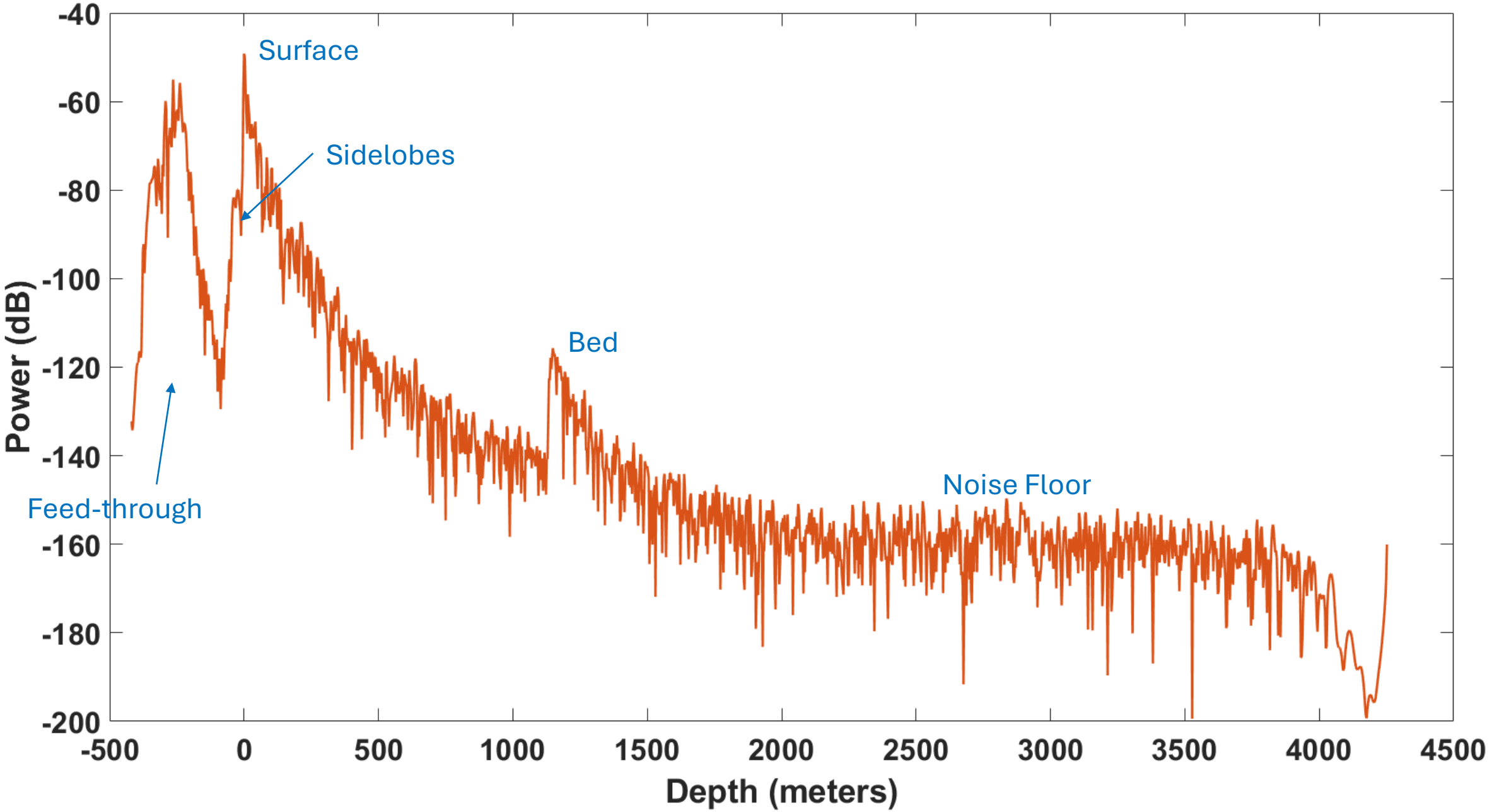
Range Compression – Raw Radar Trace



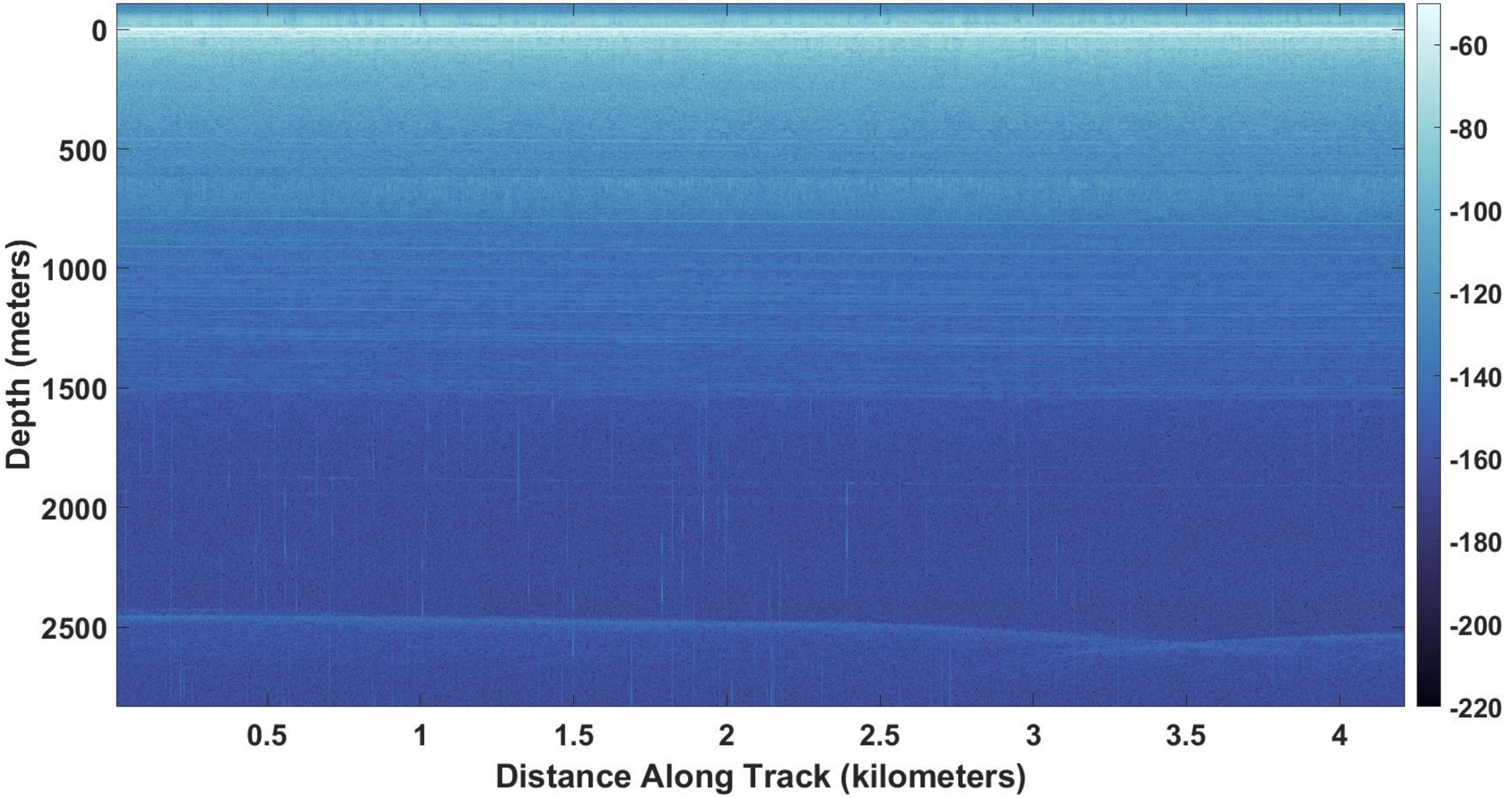
Range Compression – Rough Topography



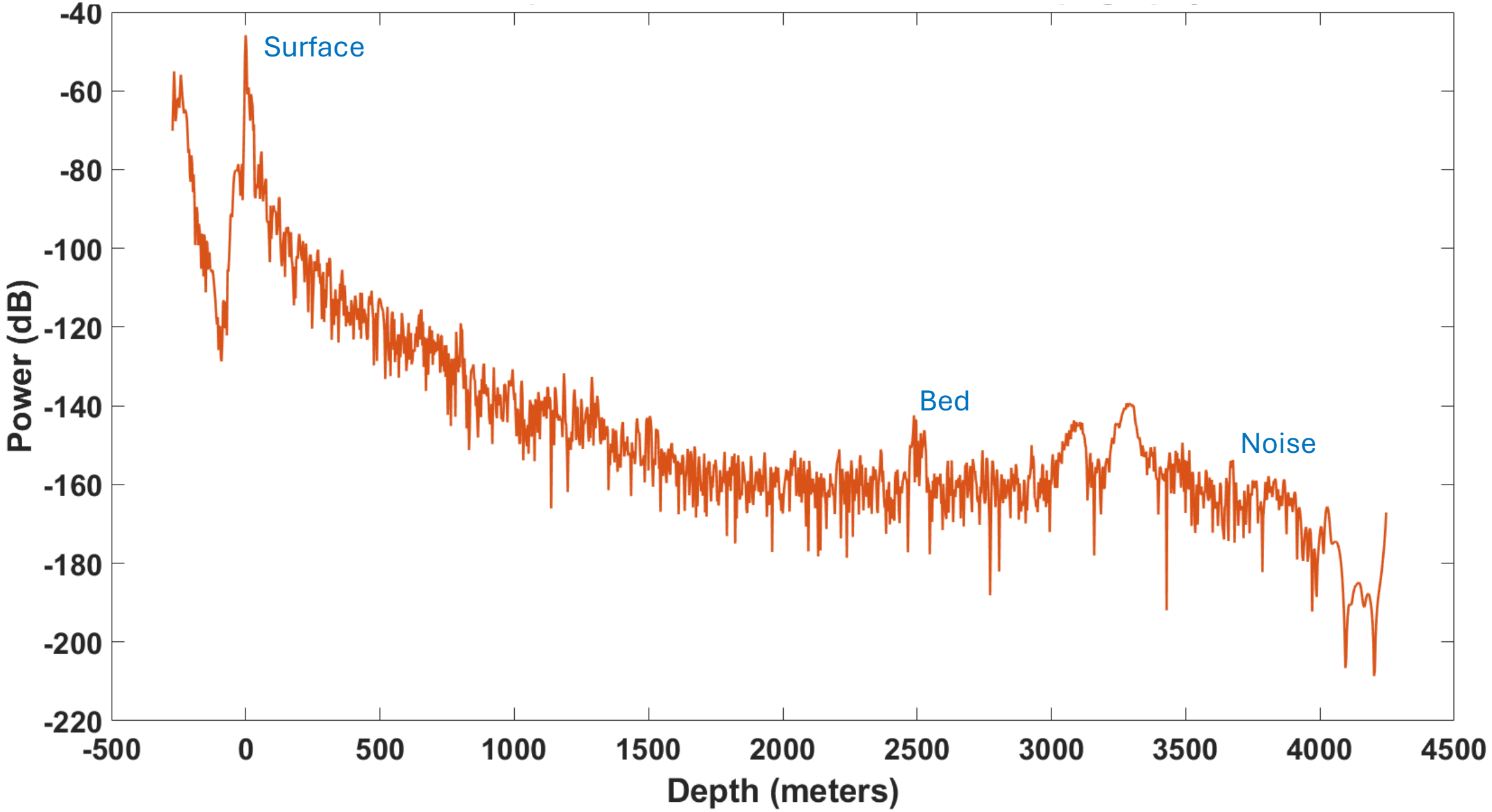
Range Compression – Rough Topography



Range Compression – Smooth Topography



Range Compression – Smooth Topography

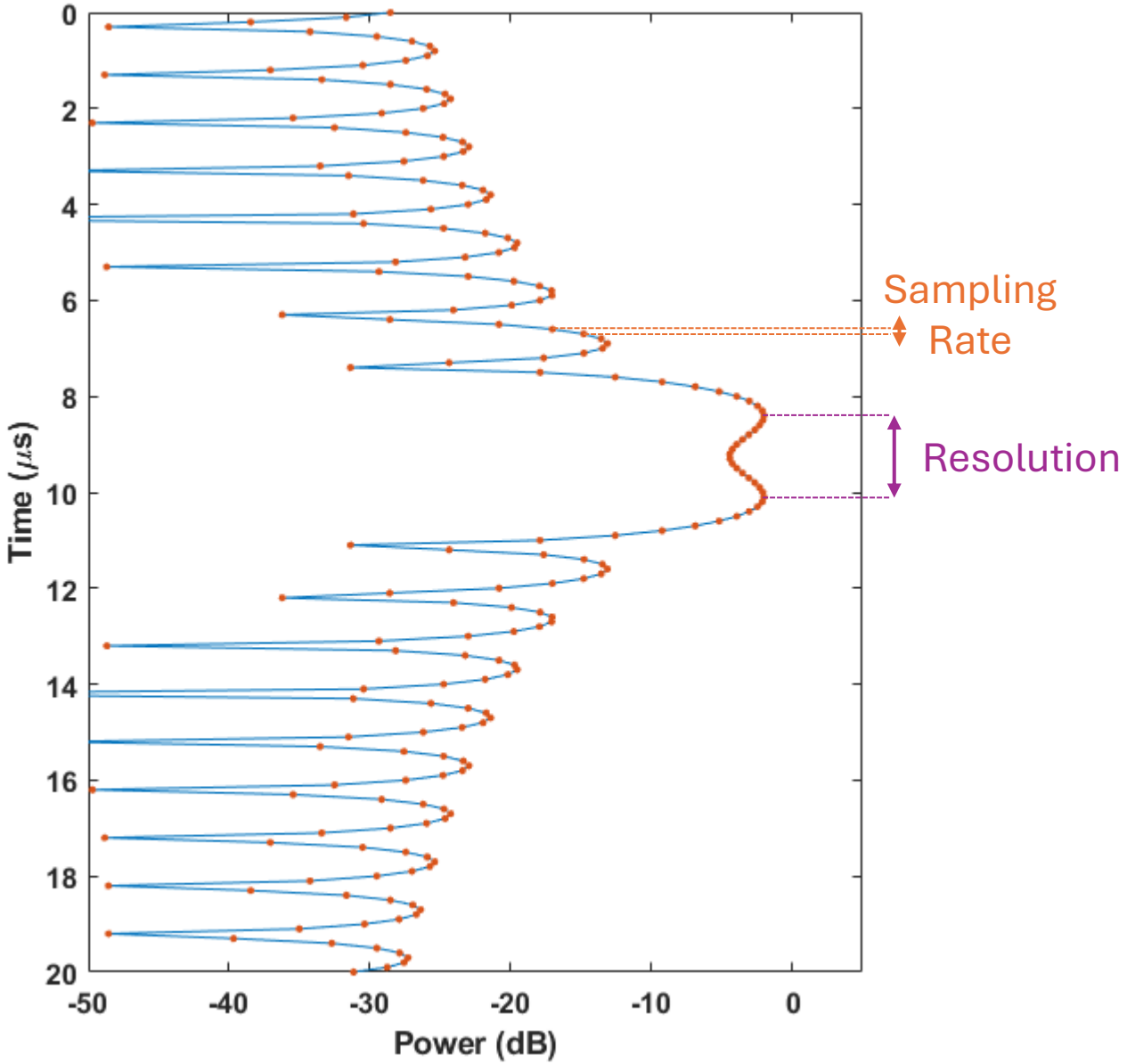


Sampling Rate vs. Resolution

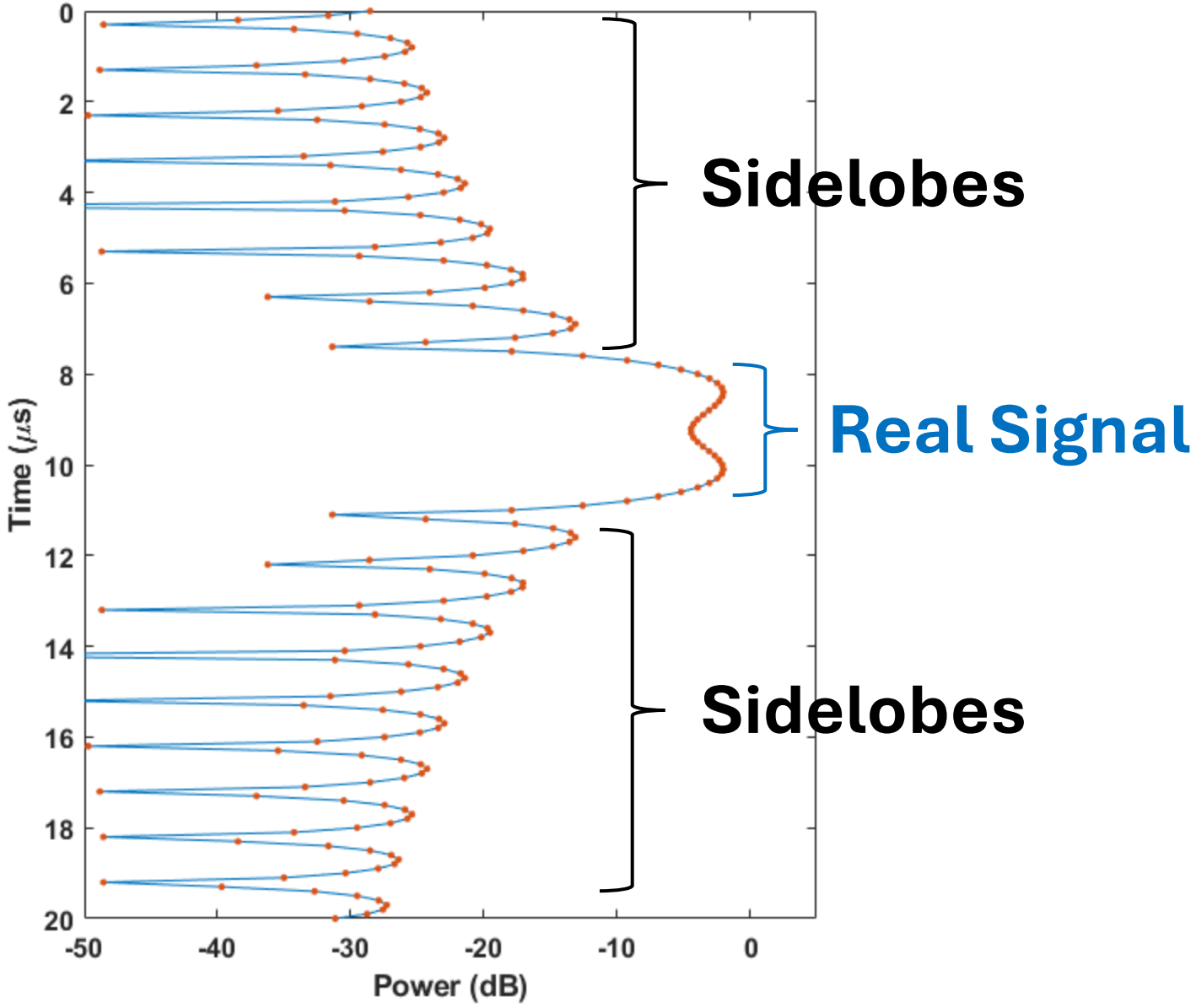
Sampling Rate: spacing in time between discrete recordings of the waveform values

Sampling Frequency: numbers of samples recorded per second

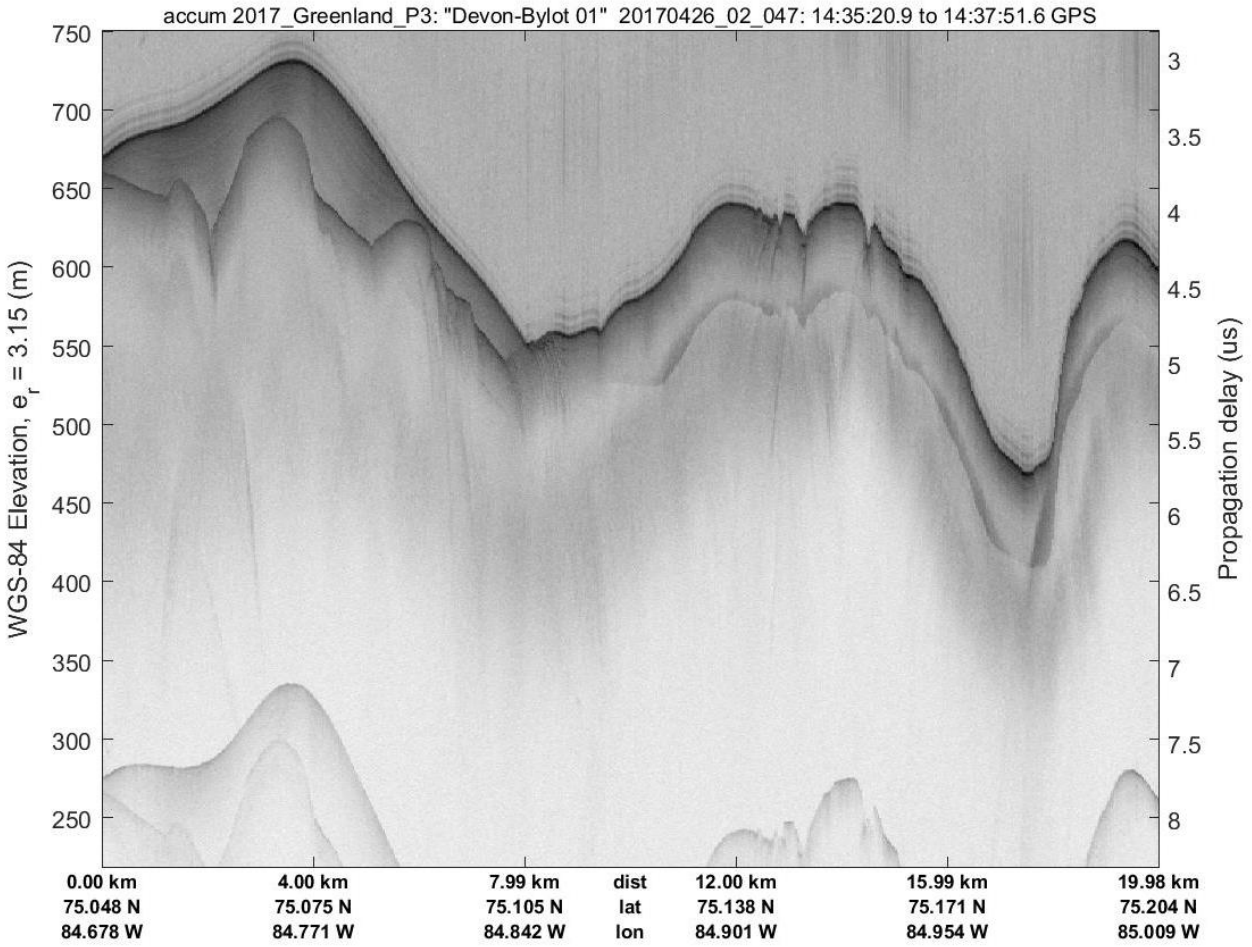
Resolution: minimum spacing between two scatters that allows us to separate their echoes in the processed waveform

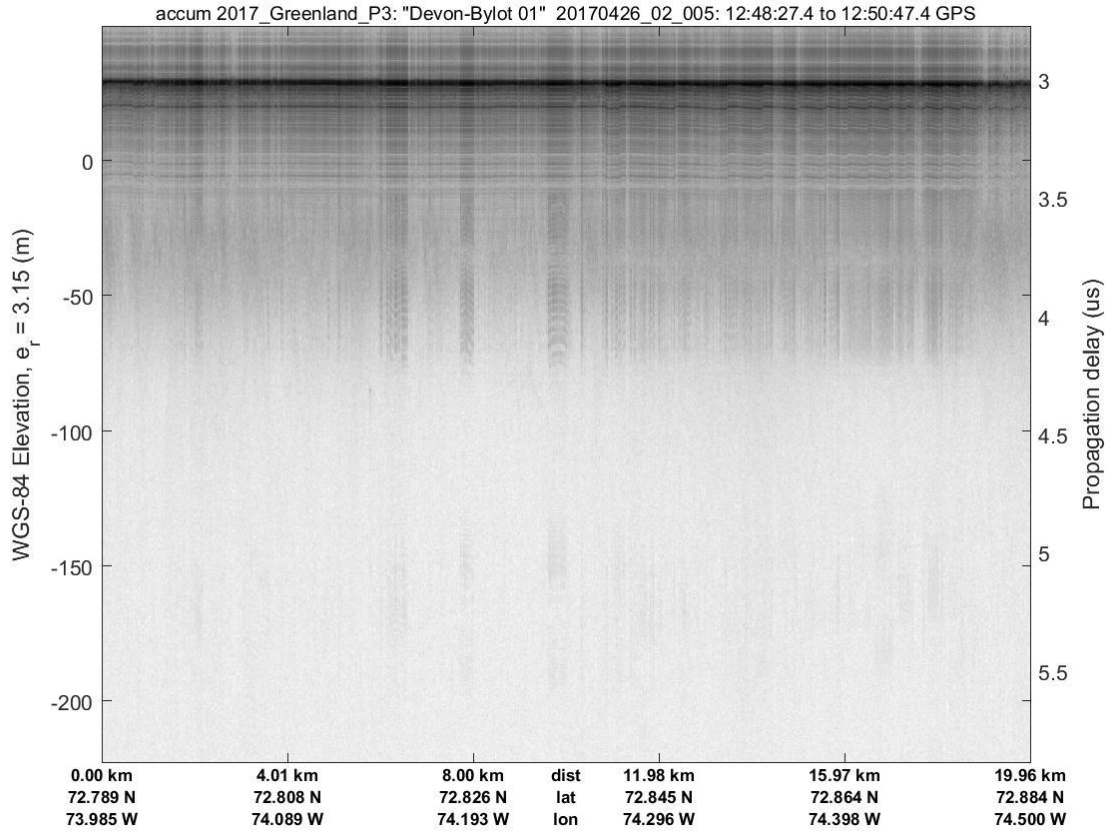


Sidelobes

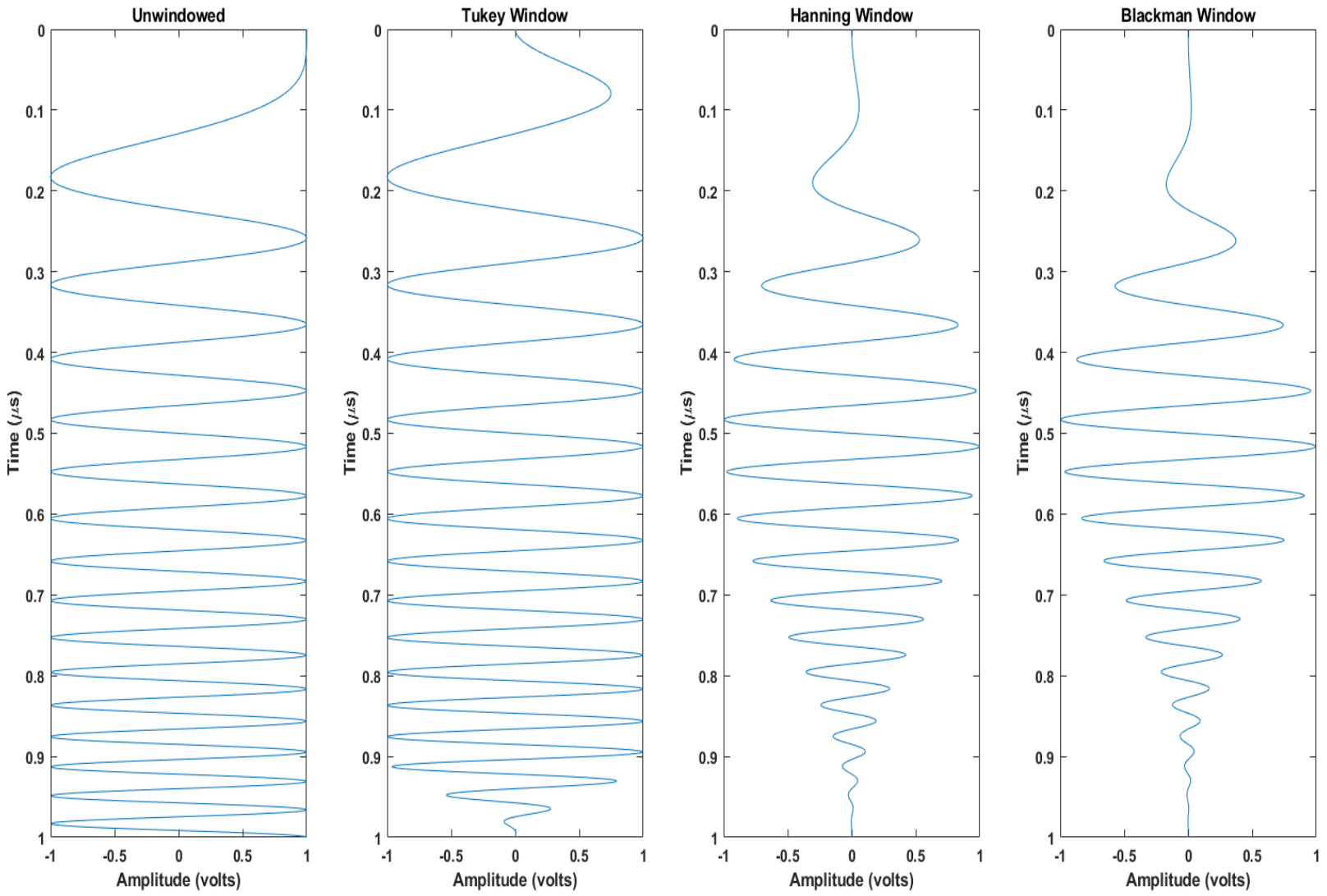

Time (μs)
0
2
4
6
8
10
12
14
16
18
20
-50
-40
-30
-20
-10
0
Power (dB)
Sidelobes
Real Signal
Sidelobes

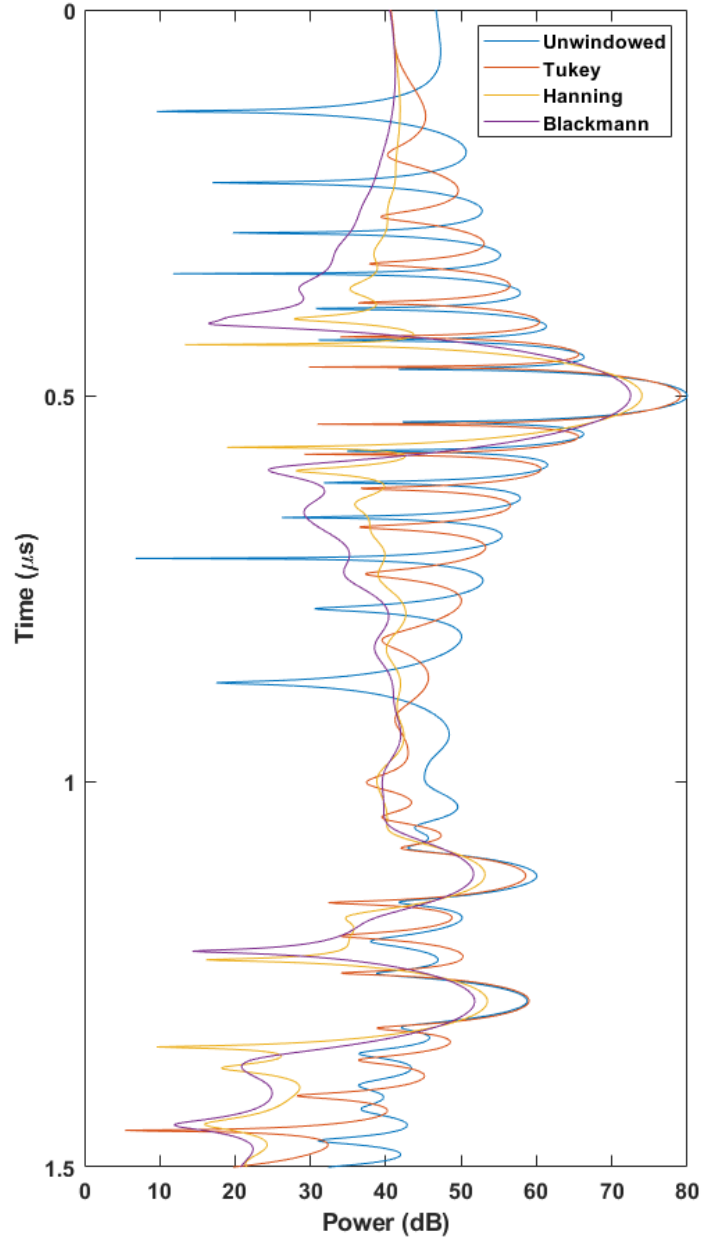
Sidelobes in 2D – Real Data





Windowing the Transmit Signal





Improving SNR & Resolution

$$\boldsymbol{SNR\ gain = B\tau w_p}$$

(time-bandwidth product)

Empirical factor that accounts for peak power reduction due to windowing

B = radar bandwidth (Hz)
τ = pulse-width
w_p = windowing factor

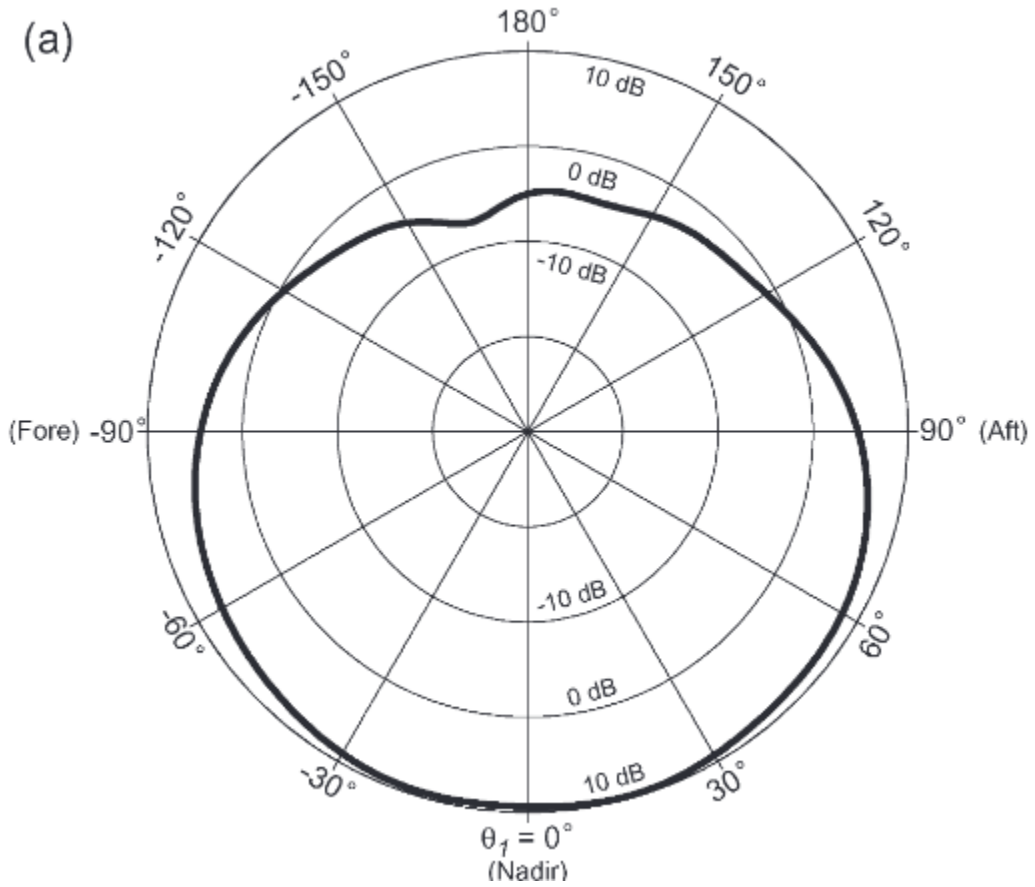
Empirical factor that accounts broadening of the peak due to windowing

$$\boldsymbol{\Delta r = \frac{c w_t}{2B}\ (\text{in air})} \qquad \boldsymbol{\Delta r = \frac{c w_t}{2nB}\ (\text{in ice})}$$

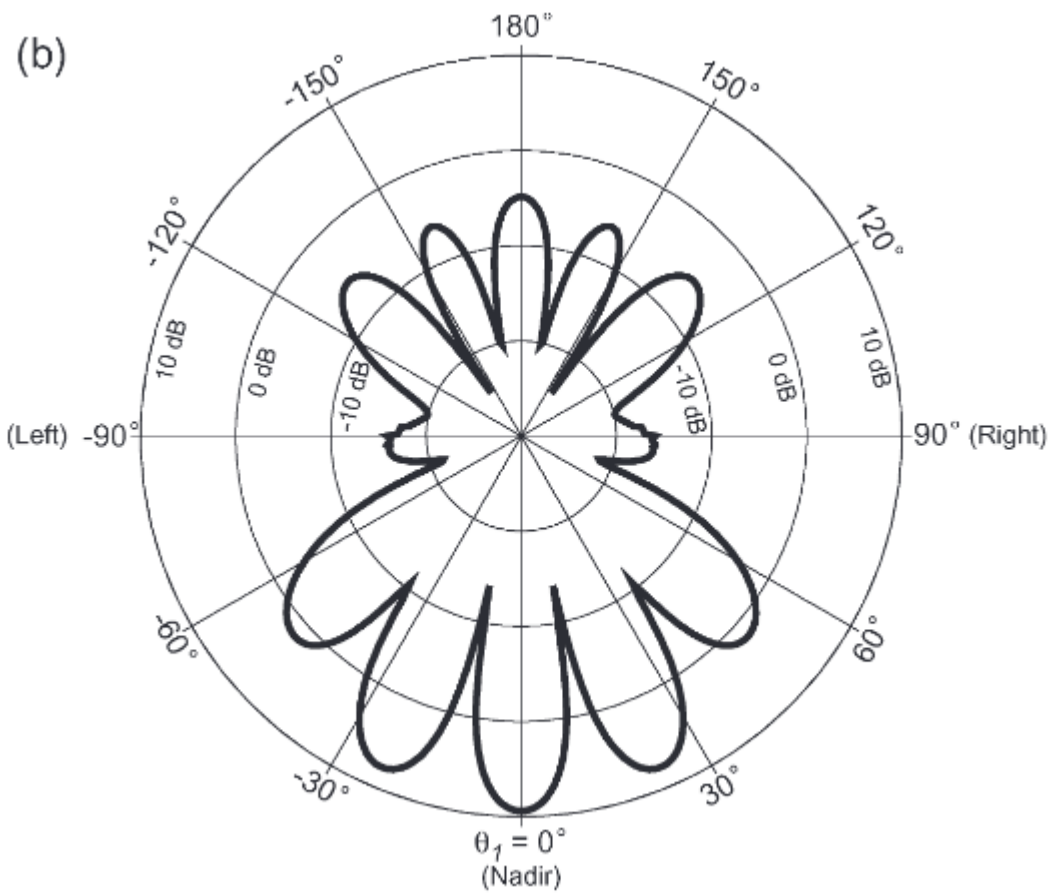
c = speed of light in vacuum (299,792,458 m/s)
B = radar bandwidth (Hz)
w_t = windowing factor
n = refractive index of ice (or firn or snow, etc)

Radar Antenna Beam Patterns

Along-Track

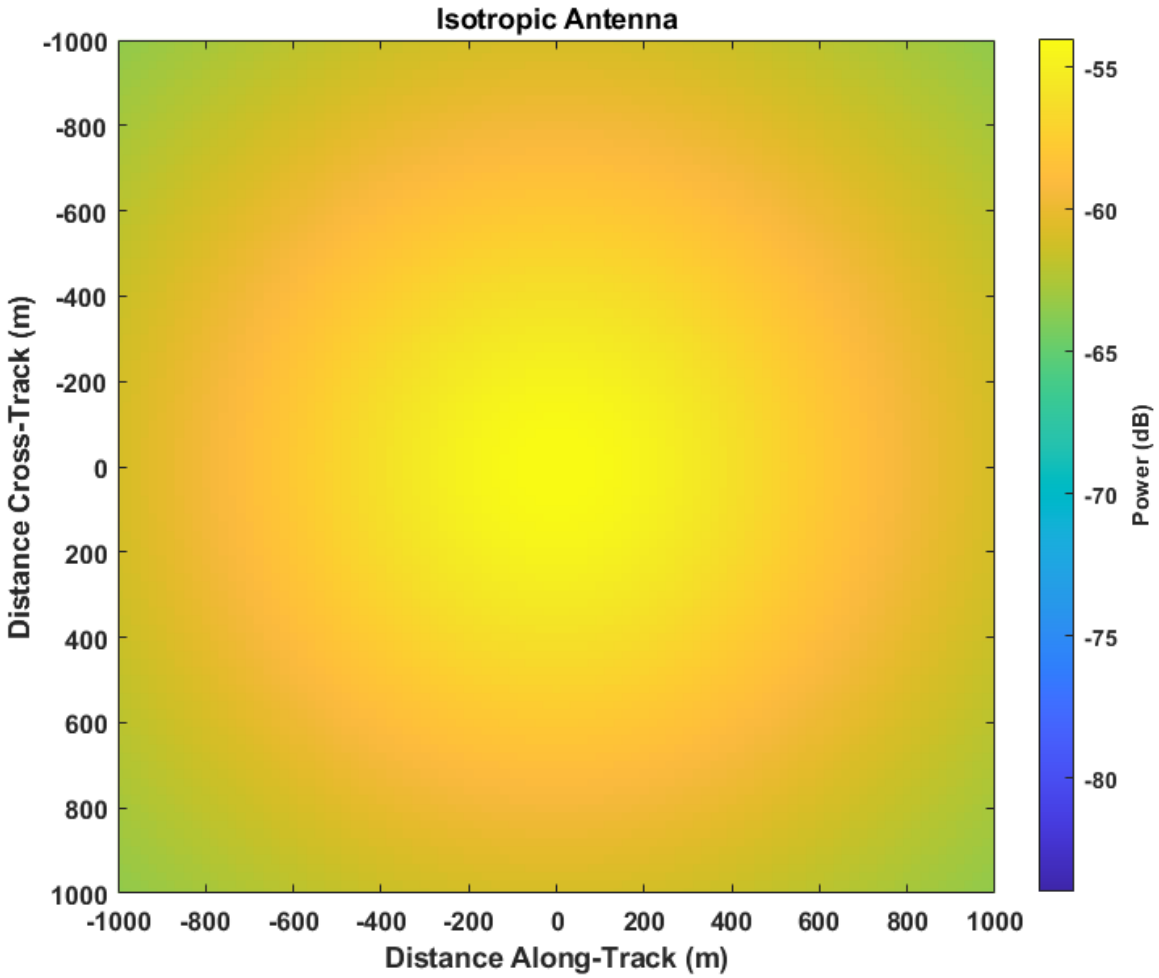


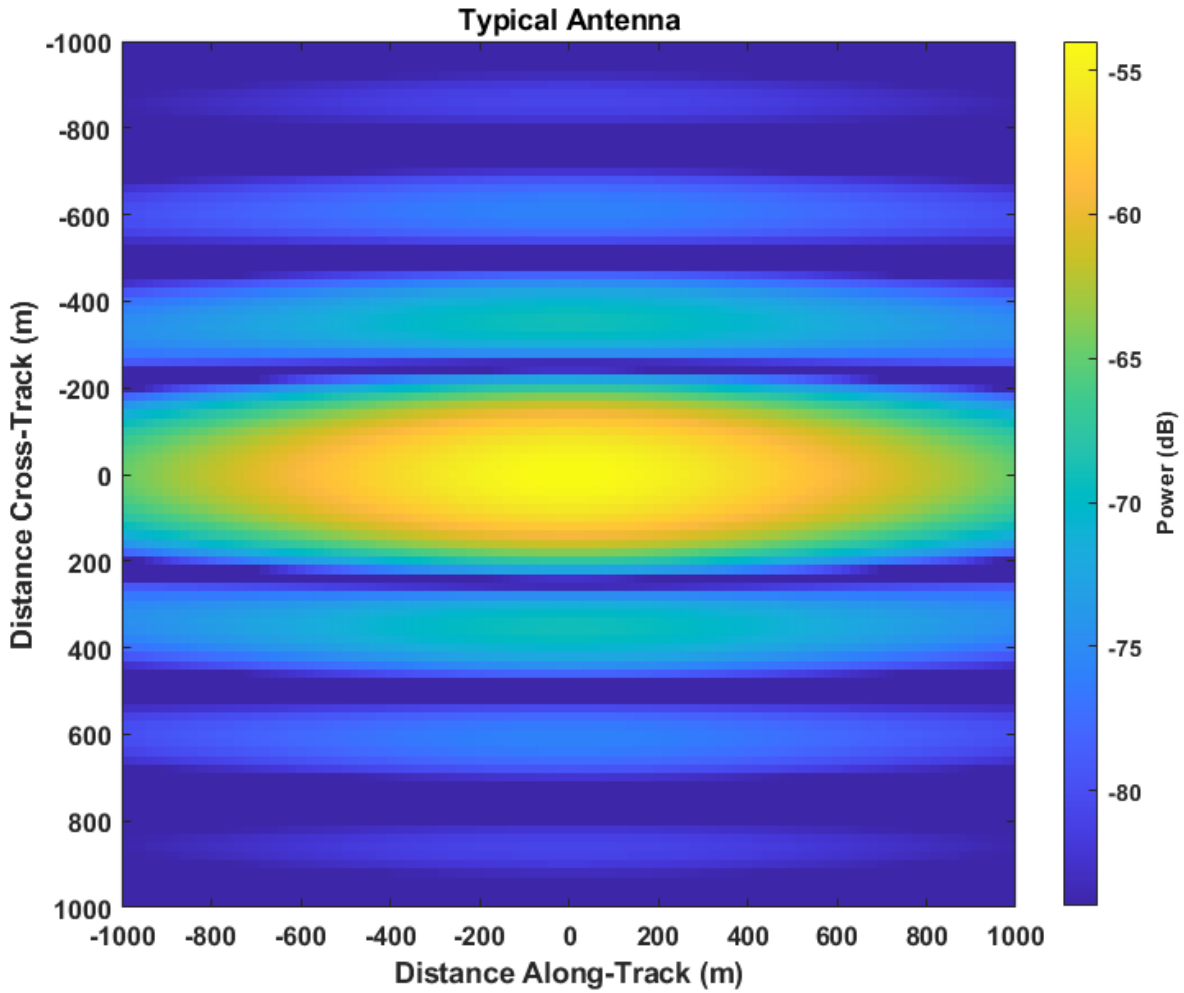
Cross-Track



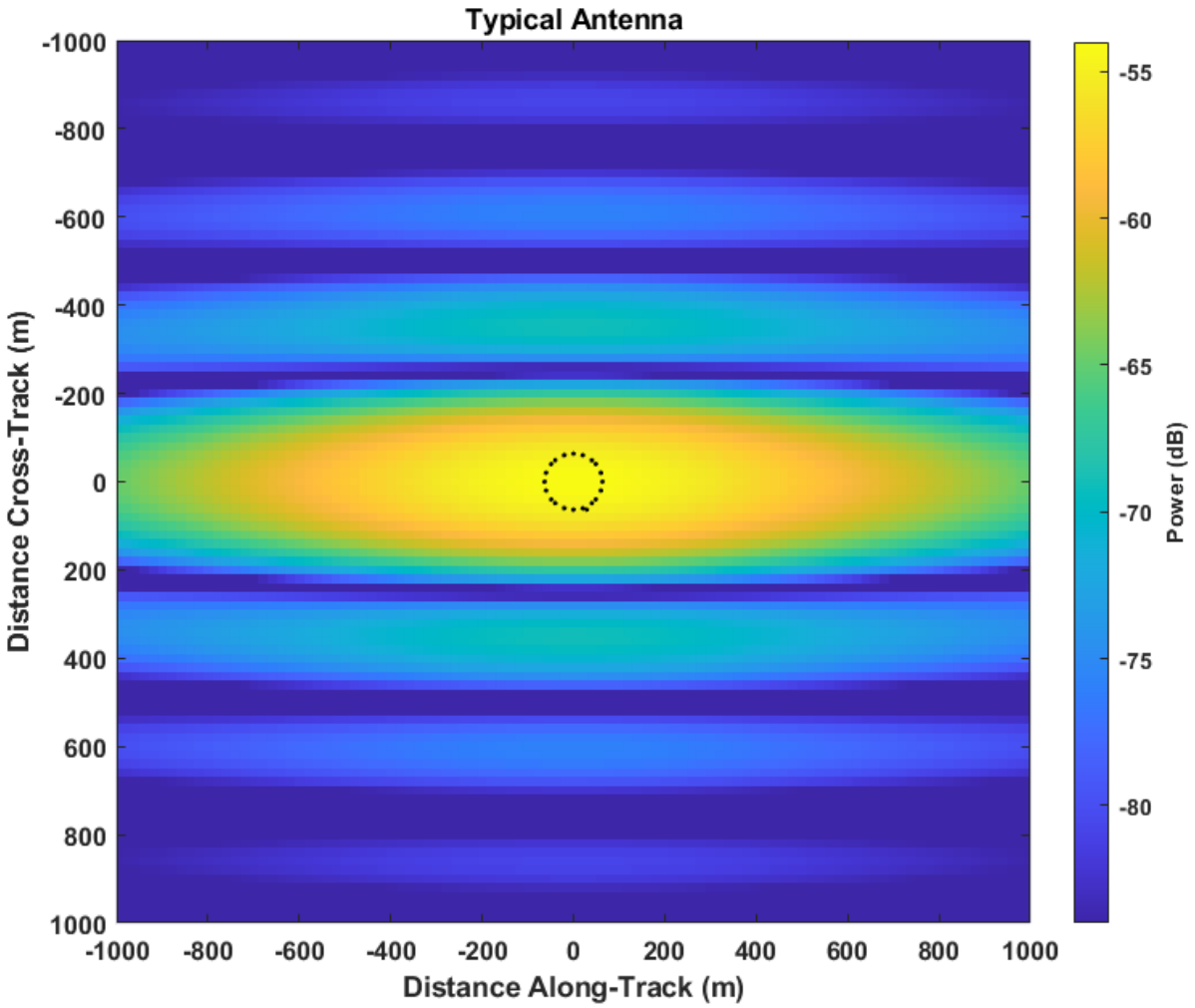
Peters et al. (2007)

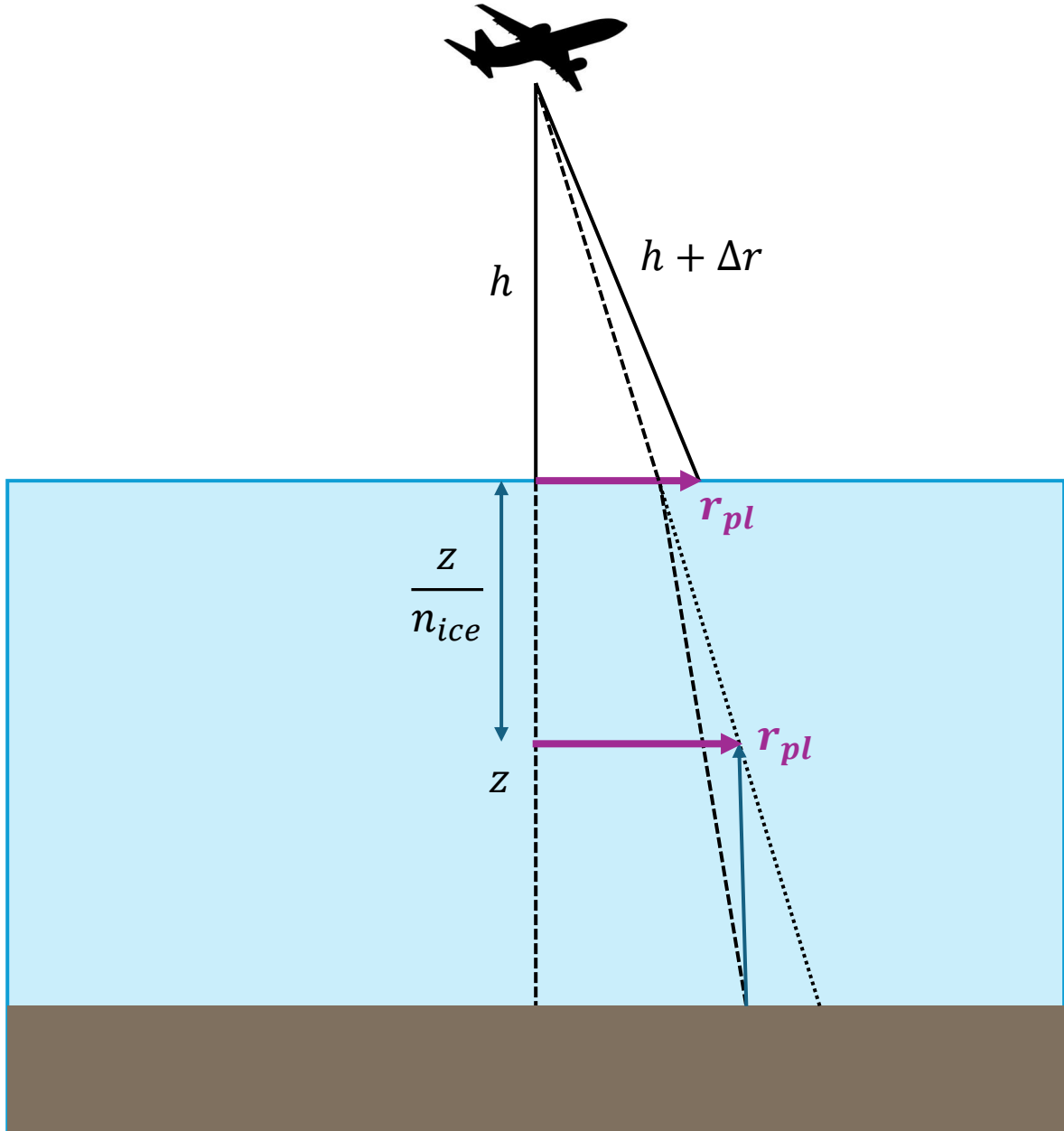
Radar Footprint on the Ground – Beam-Limited



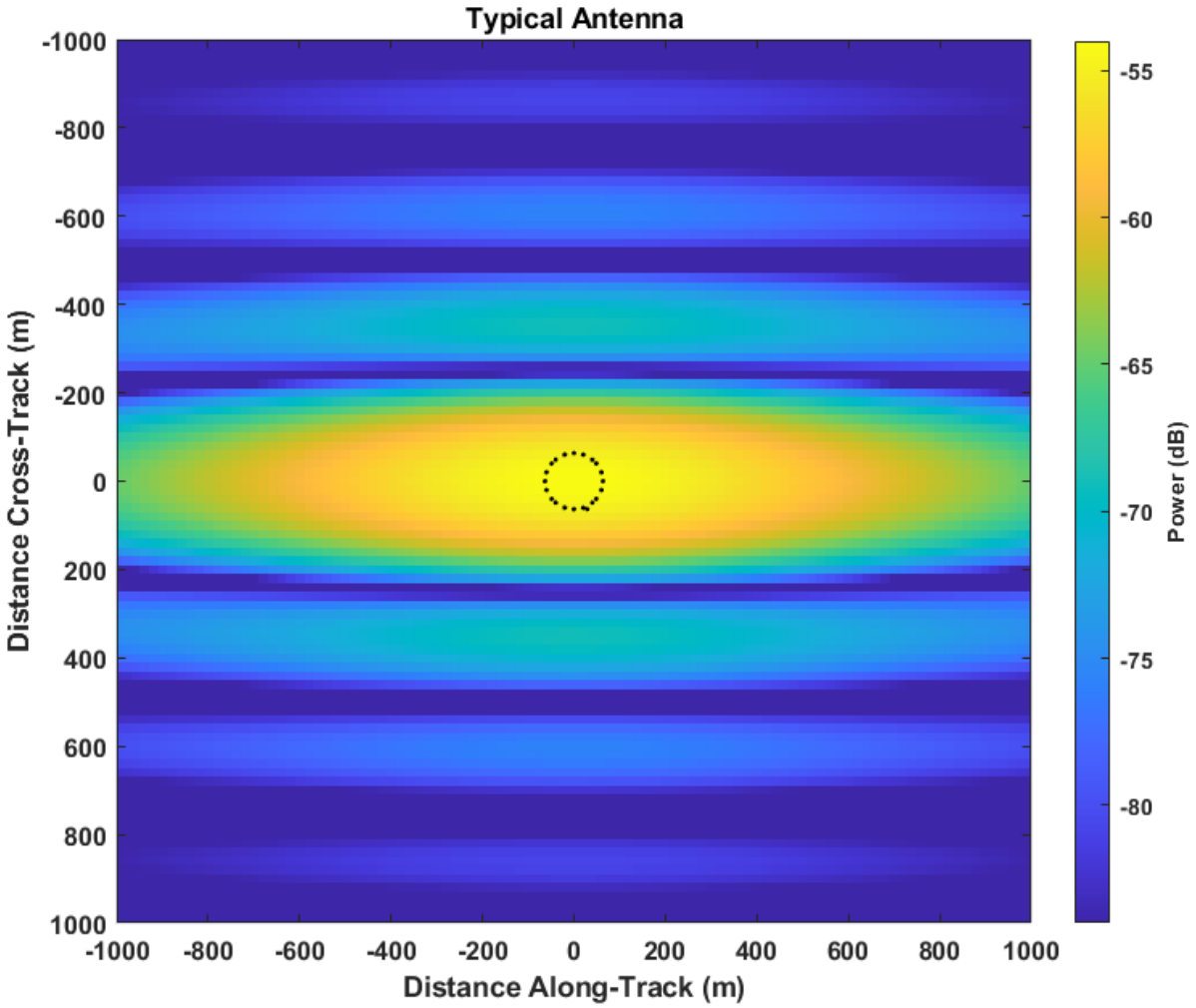


Radar Footprint on the Ground – Pulse-Limited





Radar Footprint on the Ground – Pulse-Limited

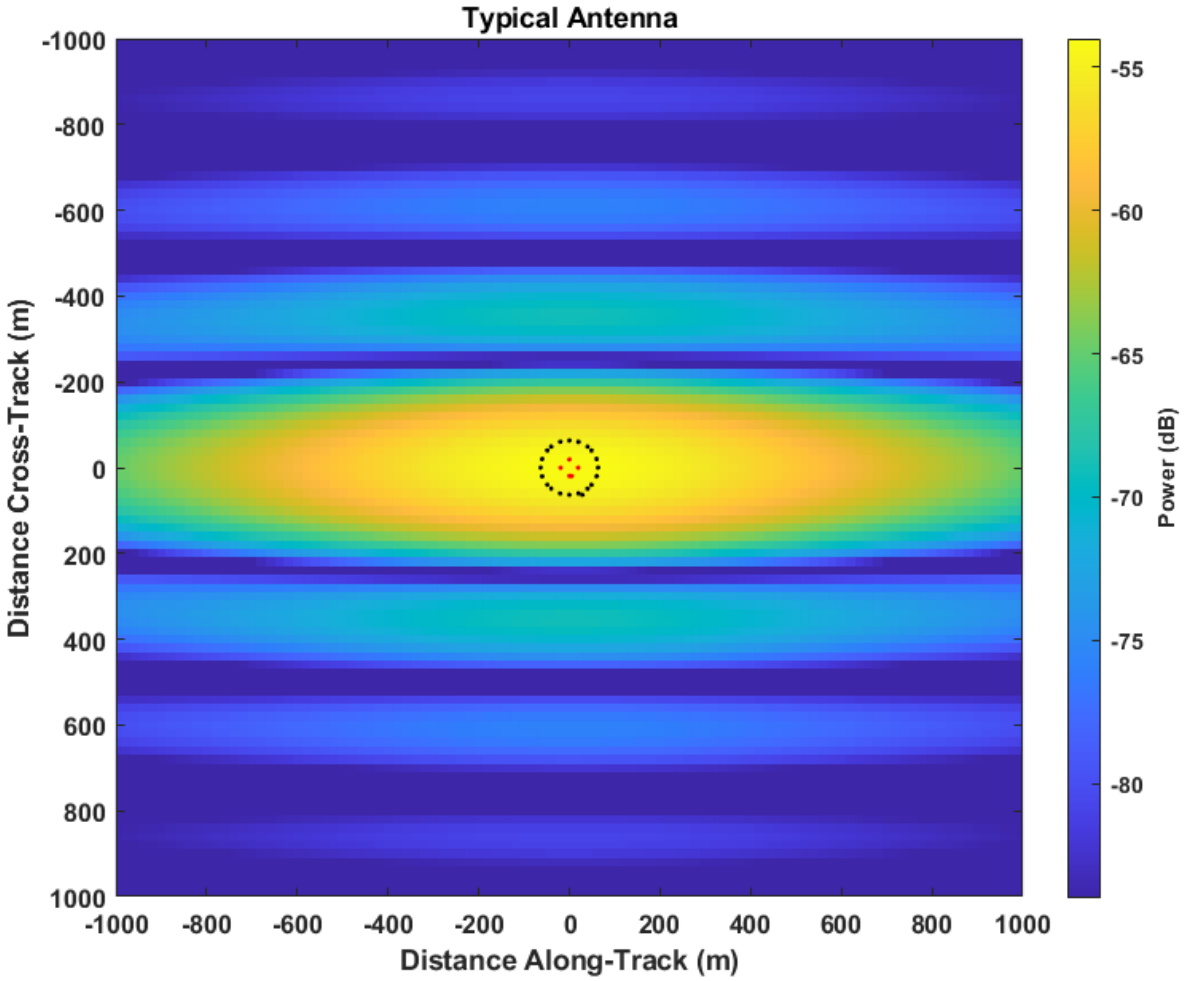


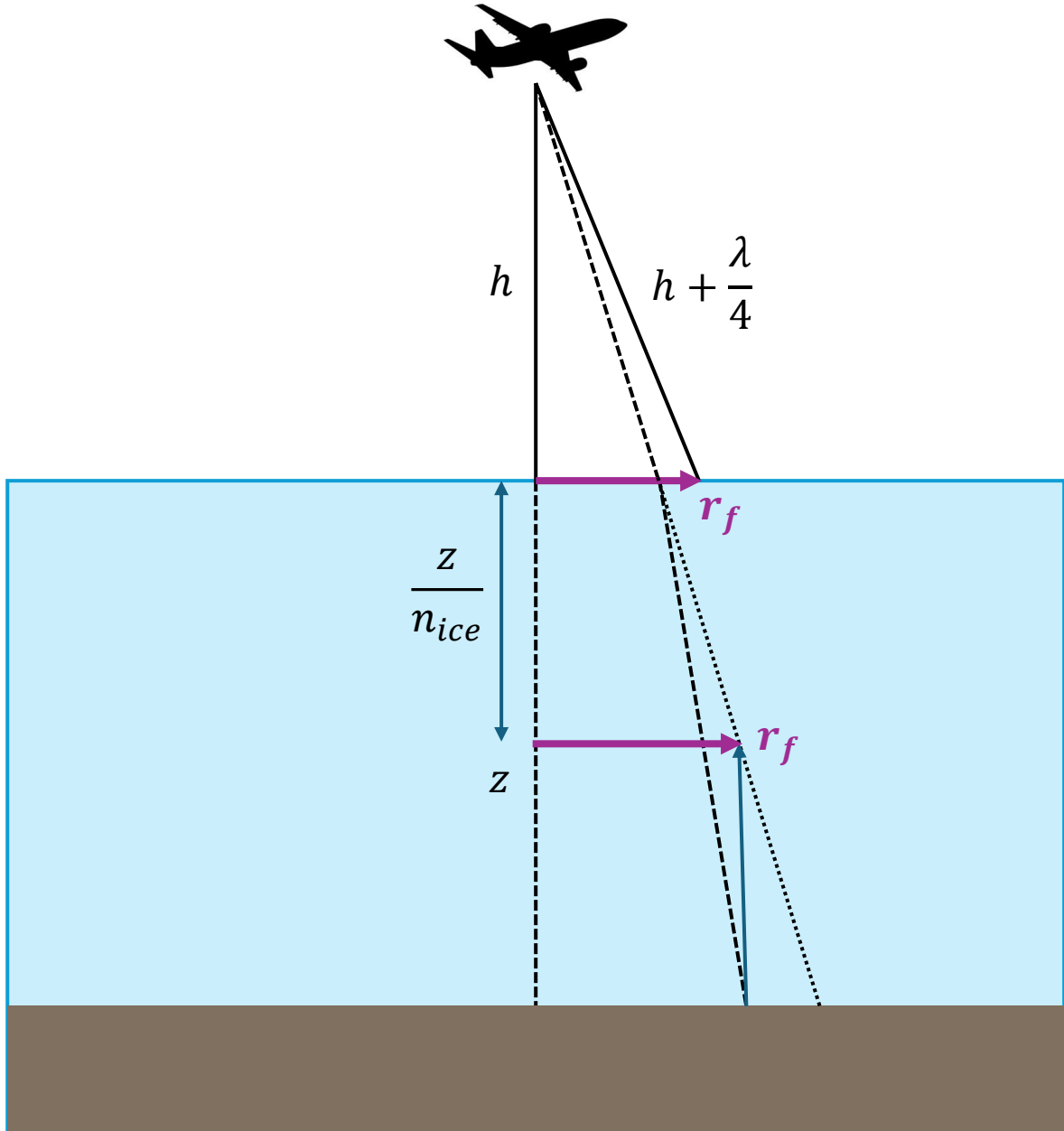
Pulse Limited Area (Rough Interface):

$$r_{PL} \approx \sqrt{2\Delta r\left(h + \frac{z}{n_{ice}}\right)}, h \gg \Delta r$$

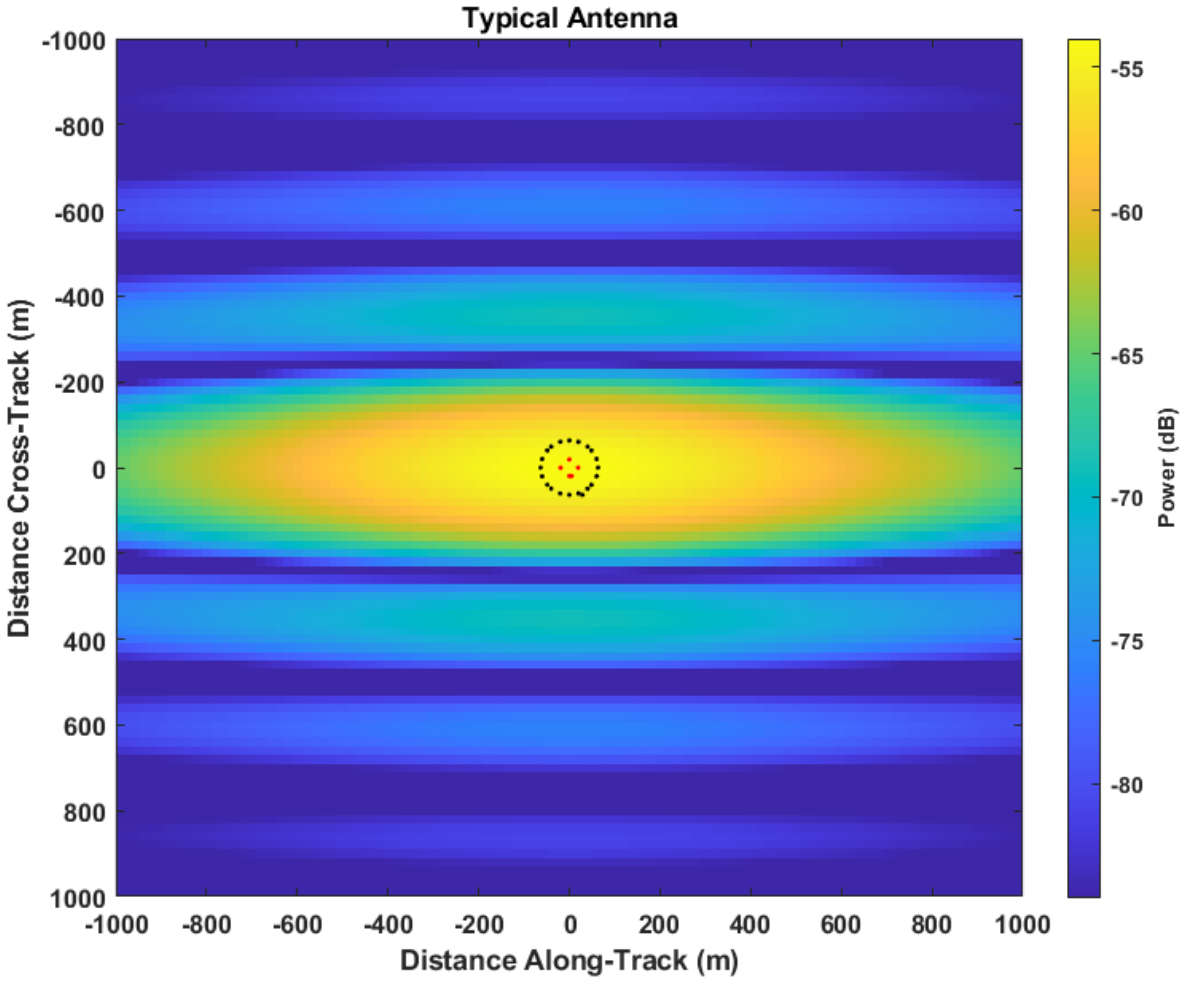
Δr = system range resolution (inversely proportional to system bandwidth)
z = depth below the surface
h = radar clearance above the surface
n_{ice} = refractive index of ice

Radar Footprint on the Ground – First Fresnel Zone





Radar Footprint on the Ground – First Fresnel Zone

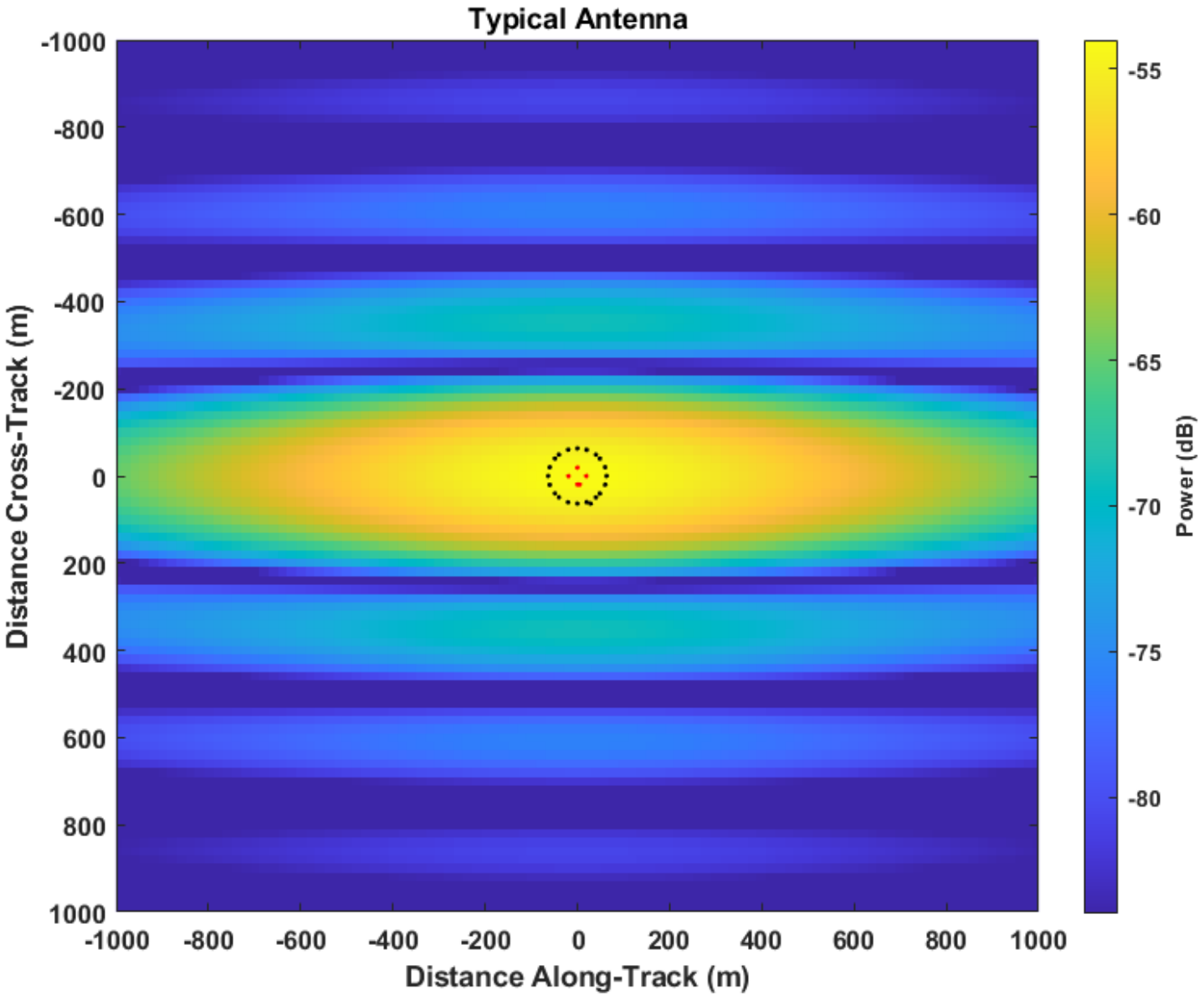


First Fresnel Zone (Smooth Interface):

$$r_f \approx \sqrt{\frac{\lambda}{2}\left(h + \frac{z}{n_{ice}}\right)}, h \gg \lambda$$

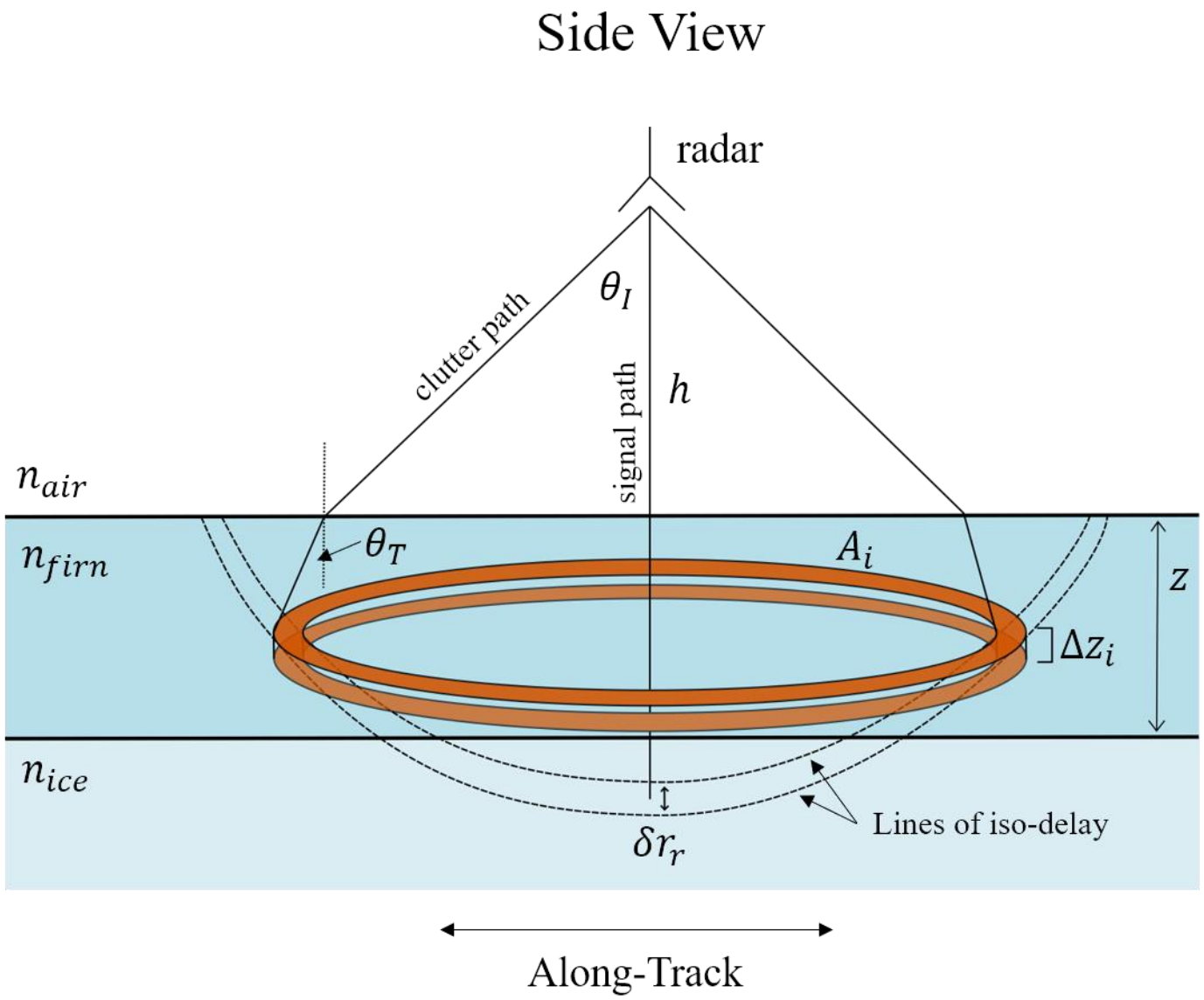
λ = radar wavelength (at the center frequency)
z = depth below the surface
h = radar clearance above the surface
n_{ice} = refractive index of ice

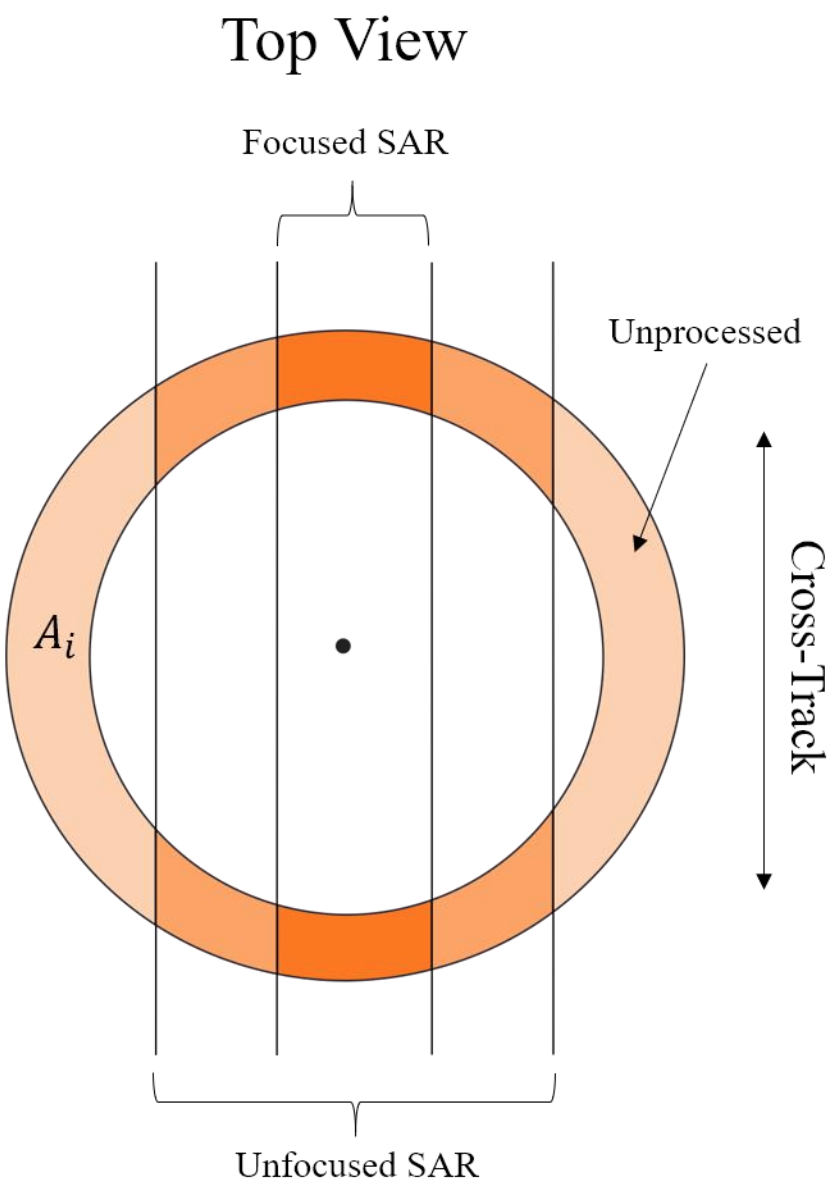
Azimuth Processing



How do we minimize off-nadir returns while preserving resolution?

Radar Sounding Geometry





Coherent Summation / Coherent Stacking / Unfocused Processing

Advantages

Improves SNR
Reduces clutter

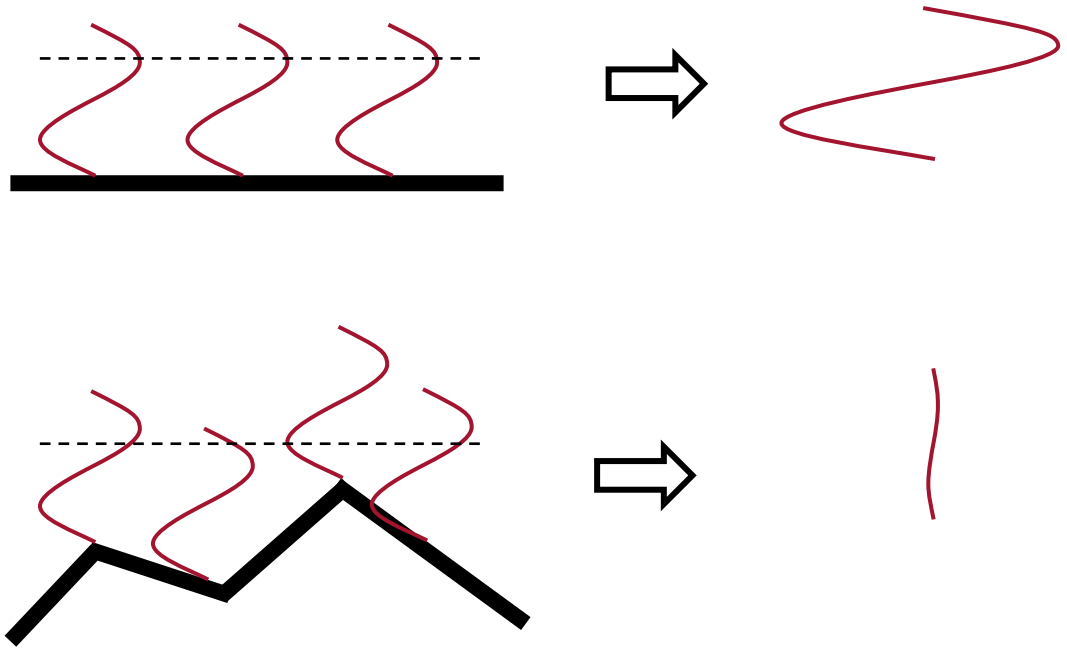
Rules of Thumb

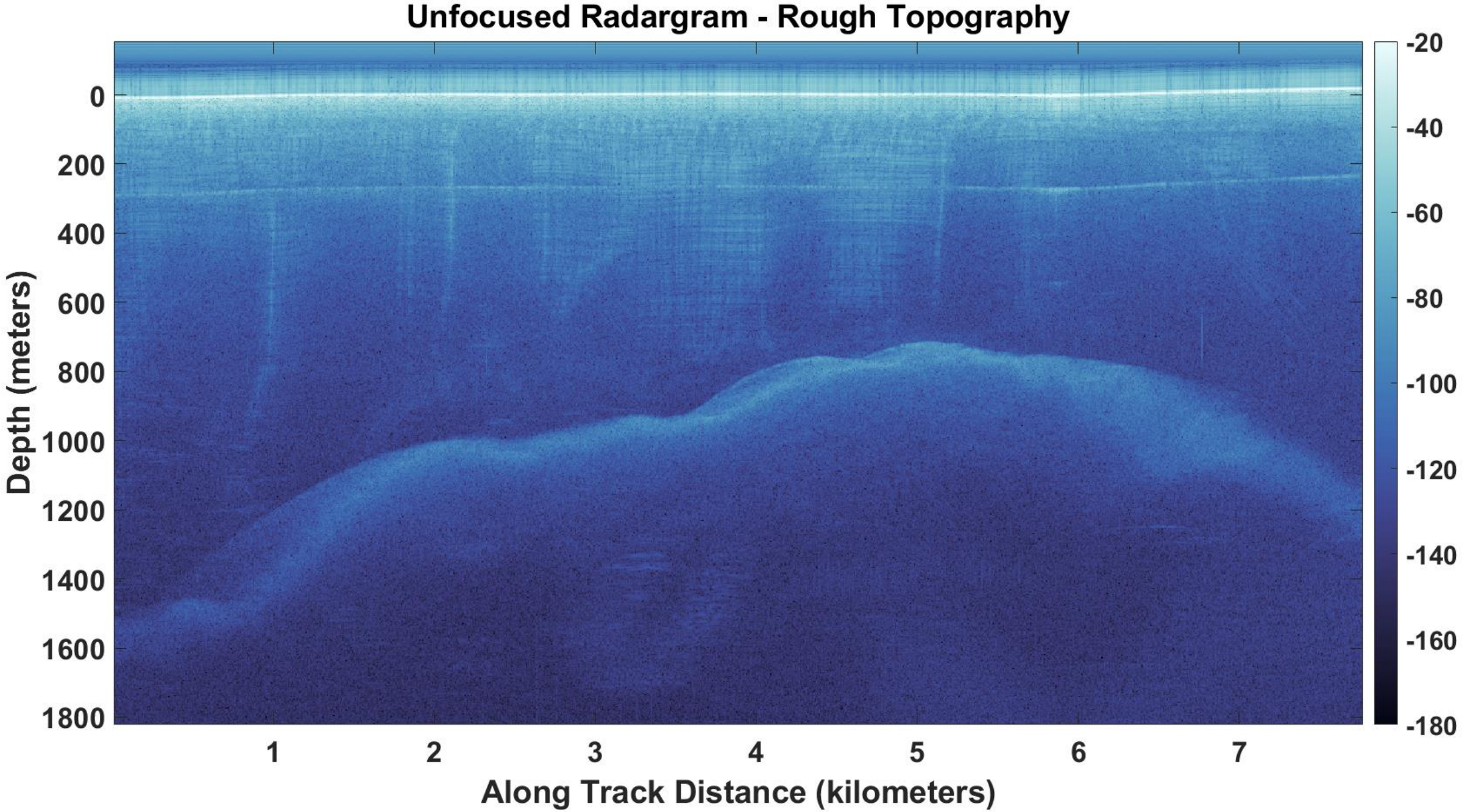
For N summations, the SNR improvement is proportional to N for coherent targets and $\sqrt{N}$ for scattering targets.

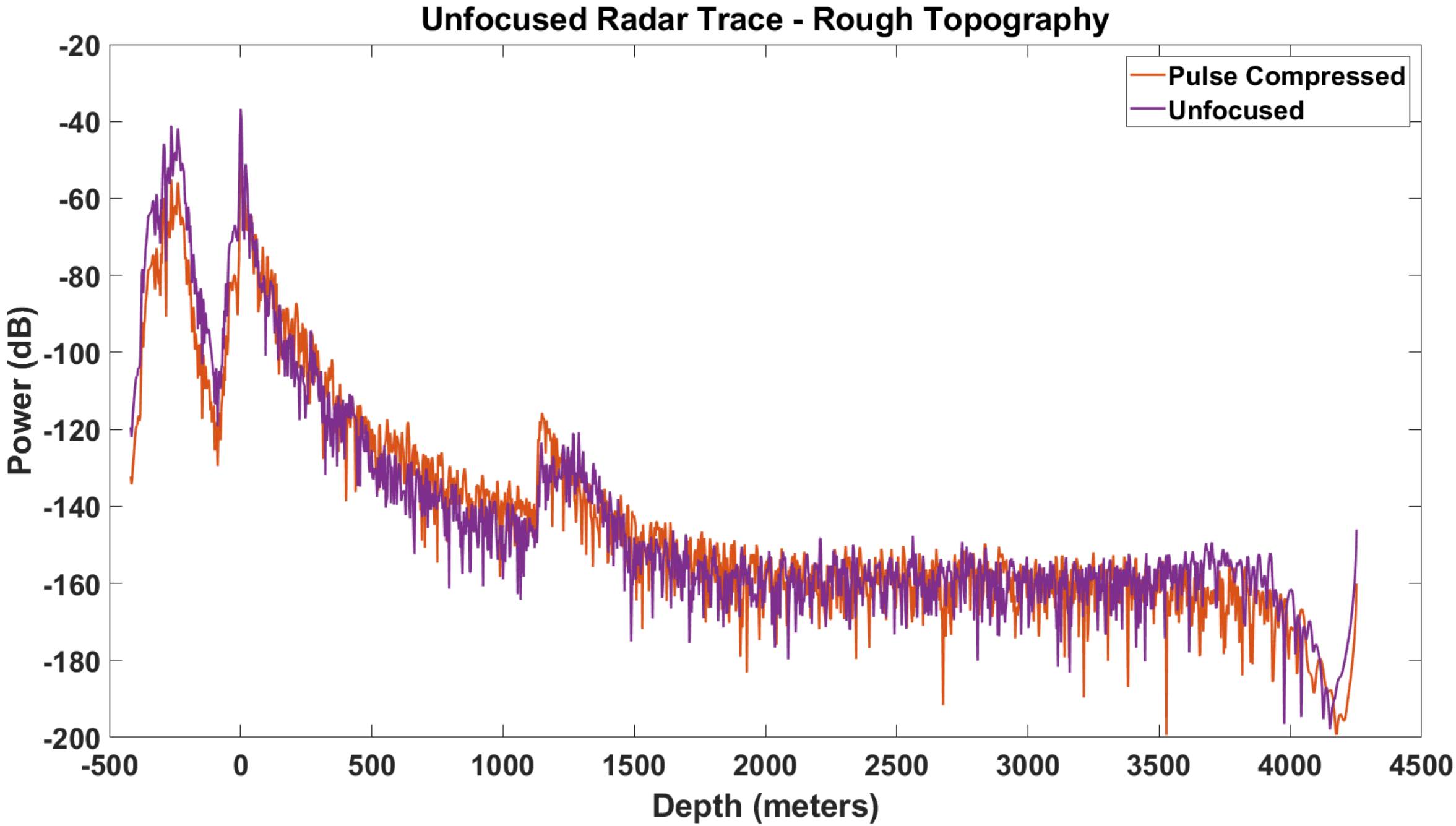
No loss of along-track resolution as long as summation is over less than the first Fresnel Zone.

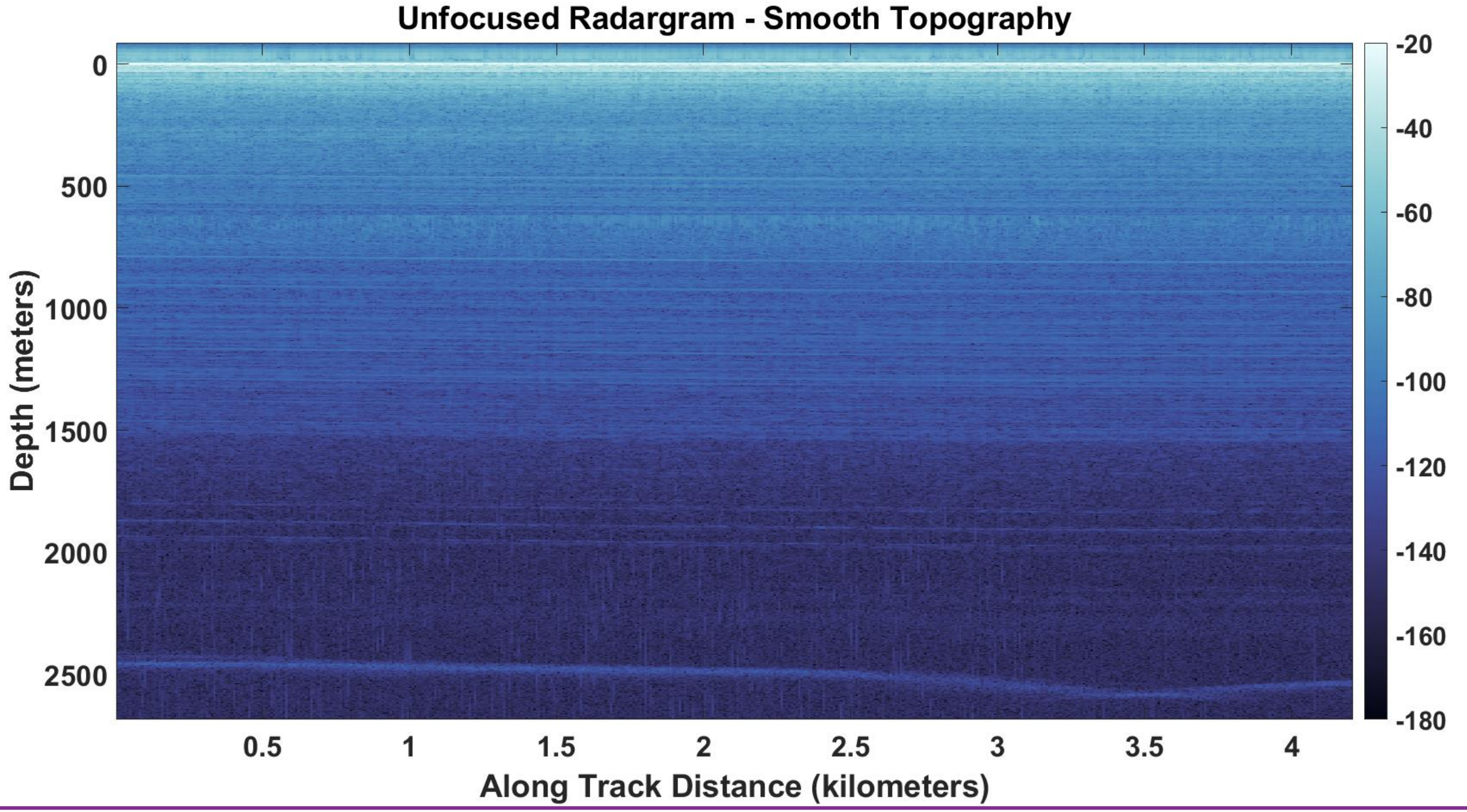
Consider motion compensation for optimal results.

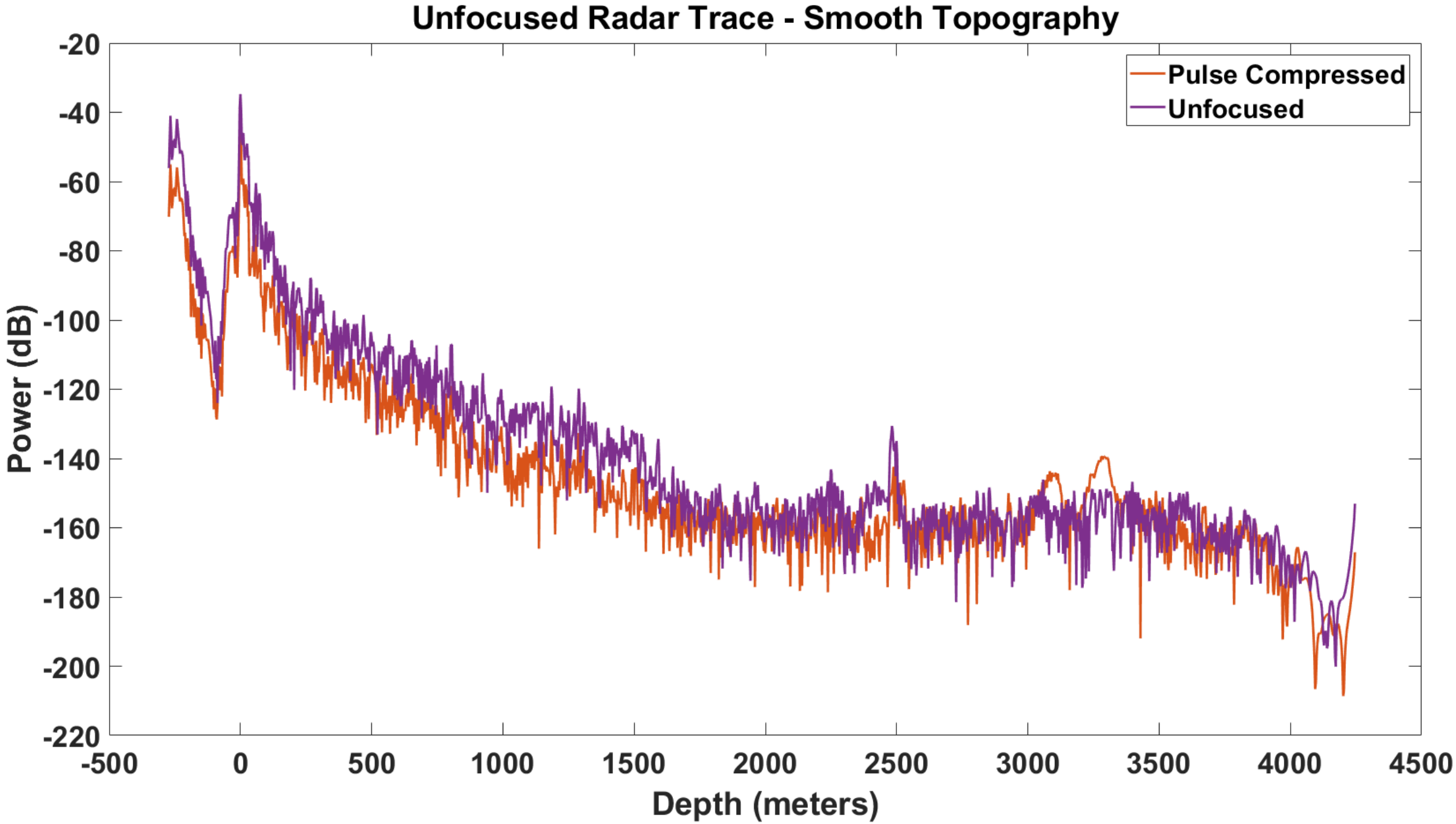
Add complex-valued (phase preserved) traces along-track




Unfocused Radargram - Rough Topography
Depth (meters)
0
200
400
600
800
1000
1200
1400
1600
1800
1
2
3
4
5
6
7
Along Track Distance (kilometers)
-20
-40
-60
-80
-100
-120
-140
-160
-180


Unfocused Radar Trace - Rough Topography
Pulse Compressed
Unfocused
Power (dB)
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-500
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Depth (meters)


Unfocused Radargram - Smooth Topography
Depth (meters)
0
500
1000
1500
2000
2500
0.5
1
1.5
2
2.5
3
3.5
4
Along Track Distance (kilometers)
-20
-40
-60
-80
-100
-120
-140
-160
-180

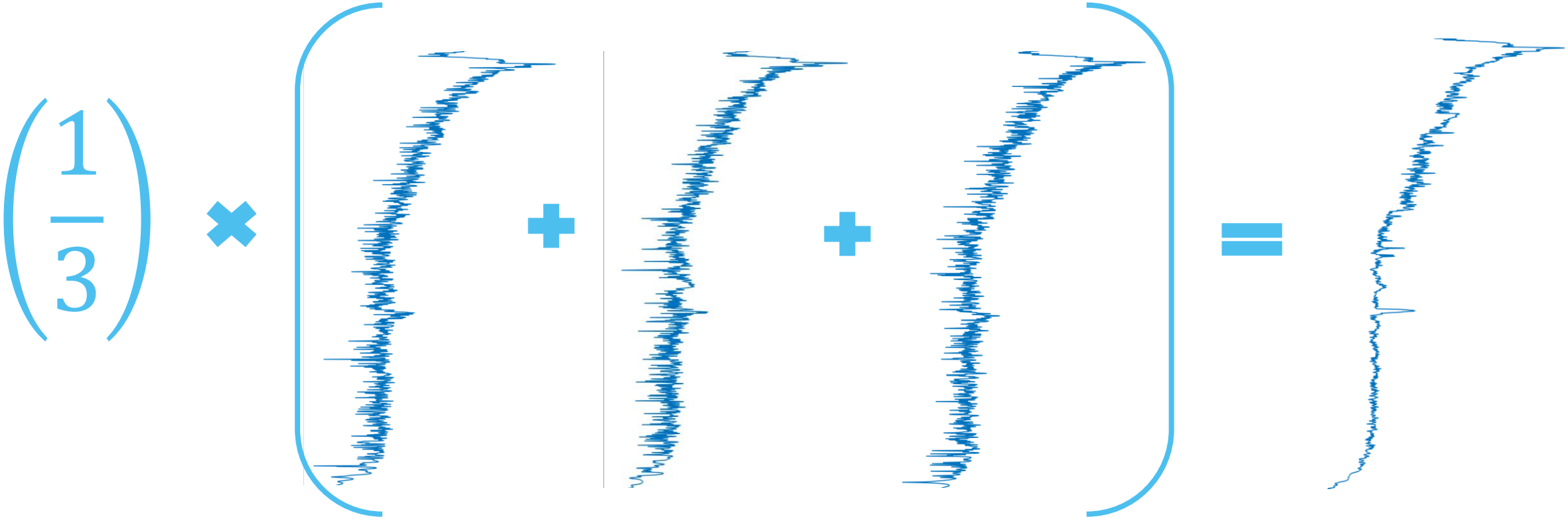

Unfocused Radar Trace - Smooth Topography
Pulse Compressed
Unfocused
Power (dB)
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-500
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Depth (meters)

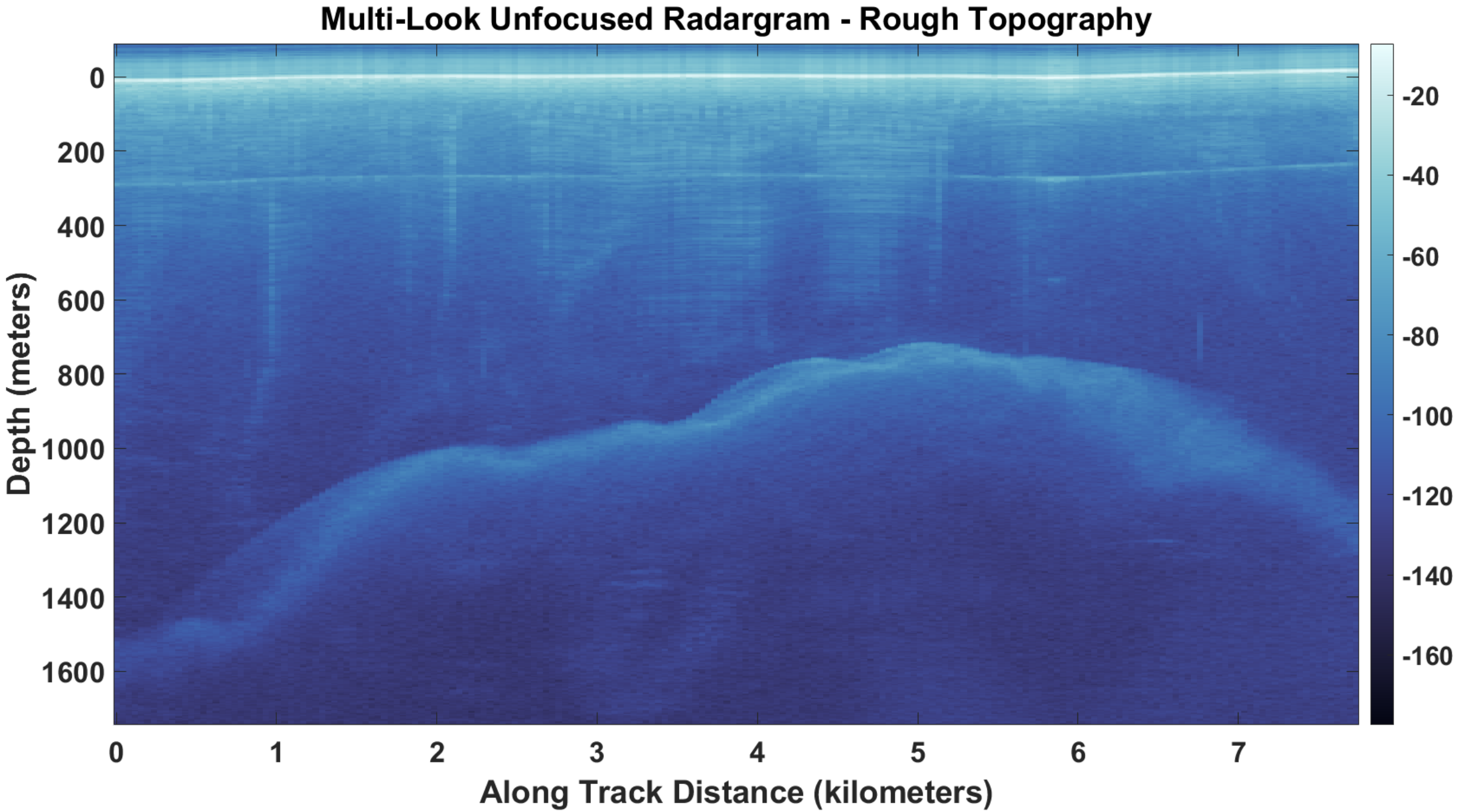
Incoherent Summation / Multilooking

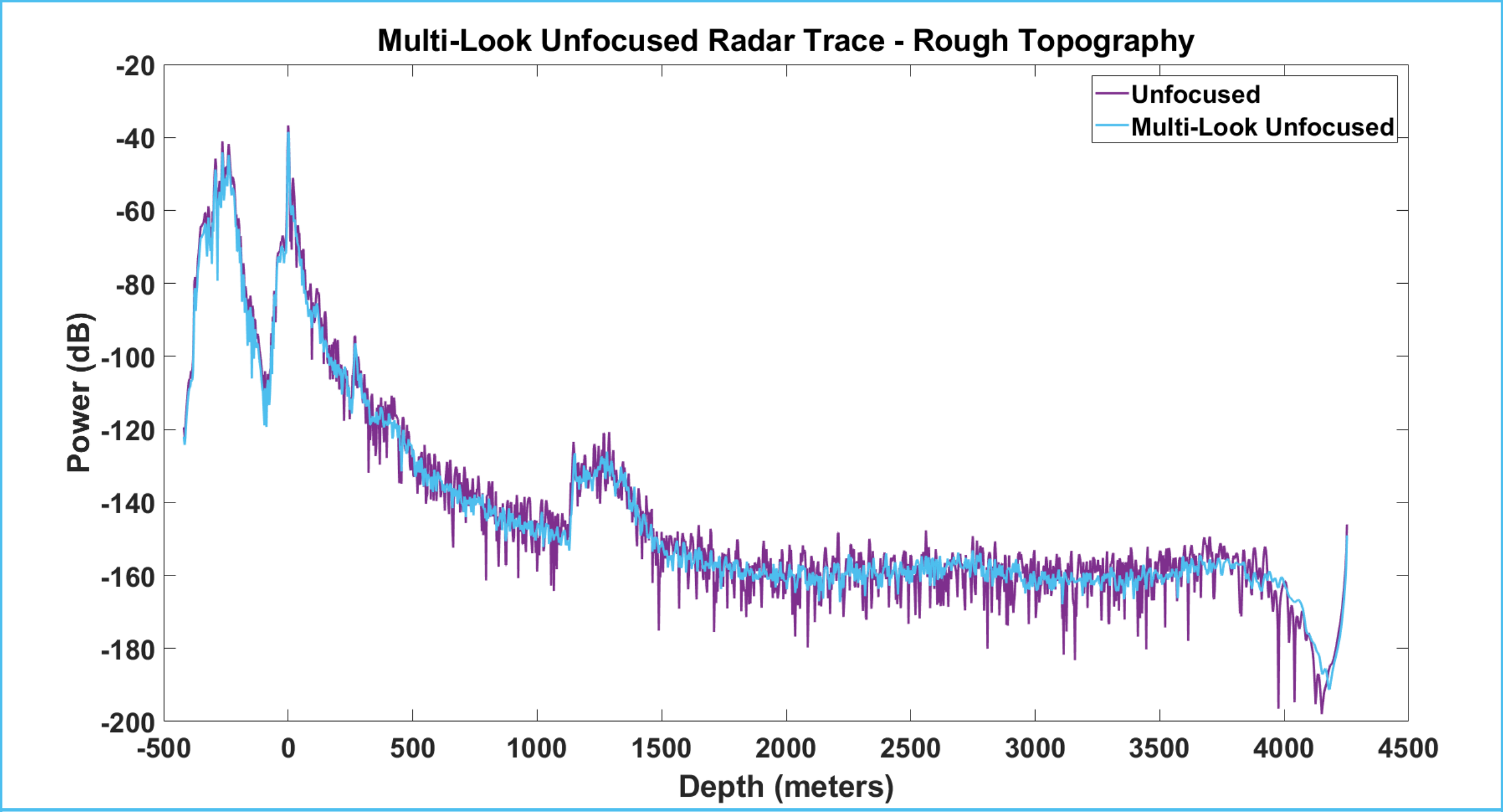
Advantages

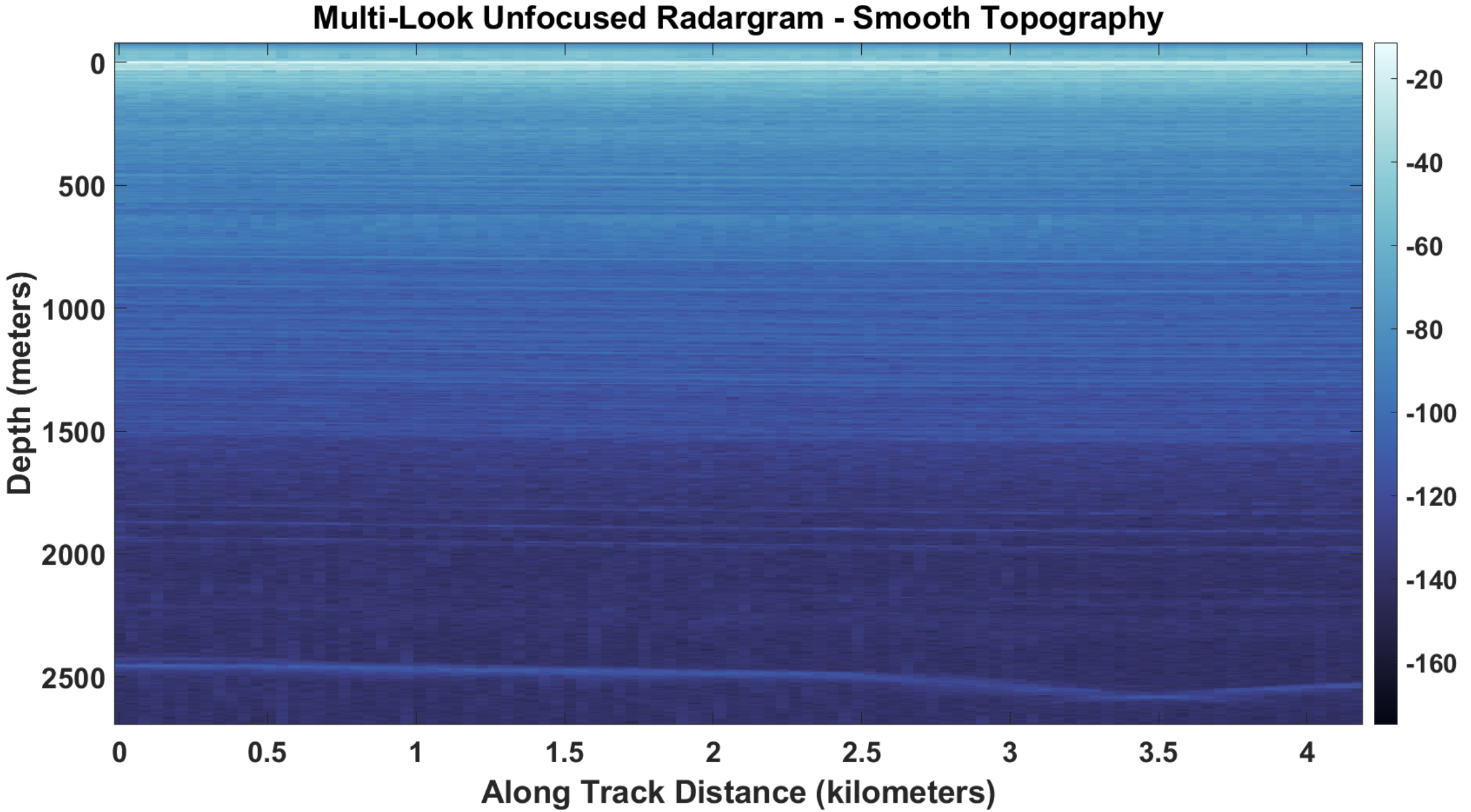
Minimizes noise variance
Smooths out speckle

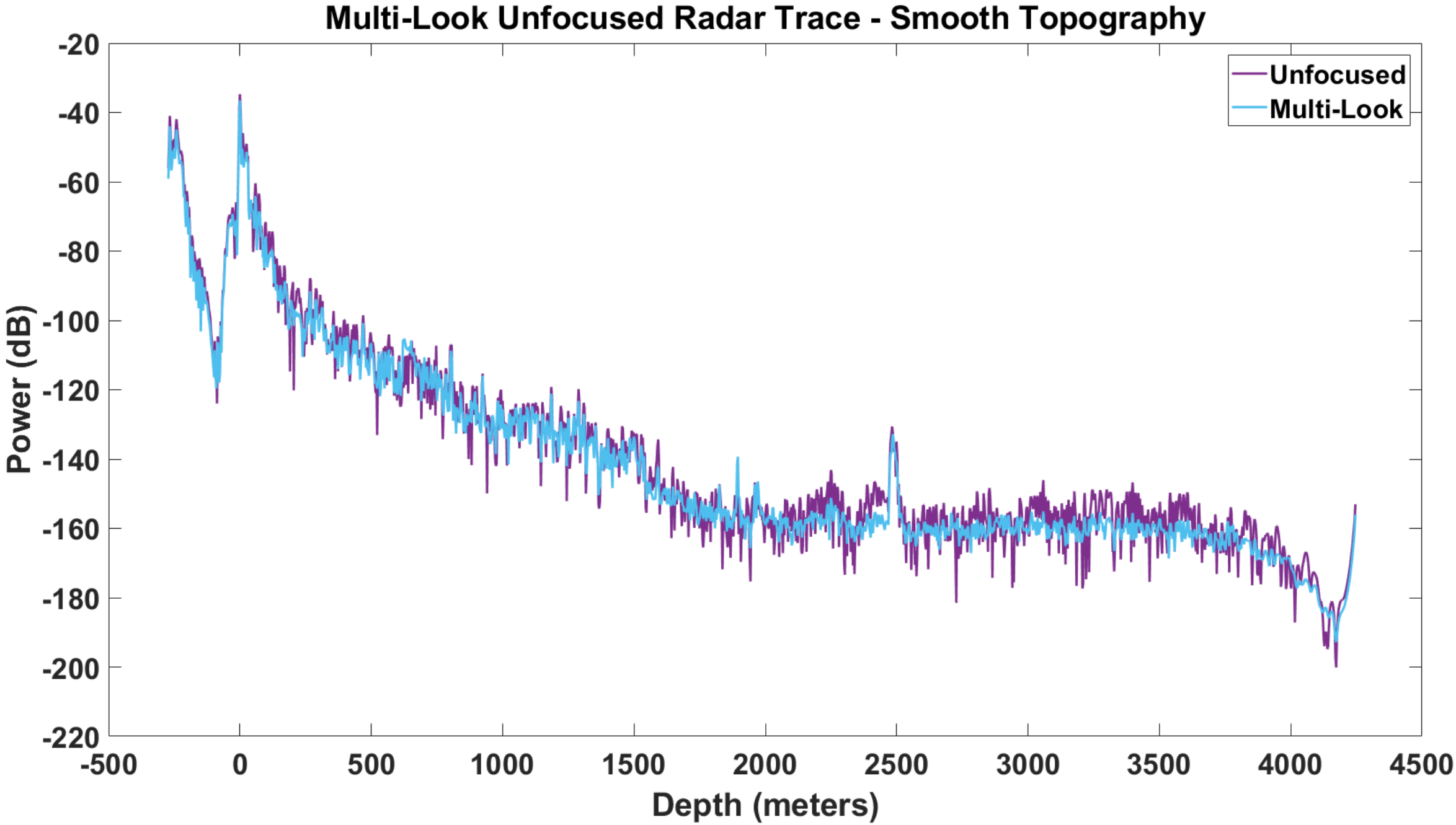
Average power-detected traces along-track




Multi-Look Unfocused Radargram - Rough Topography
Depth (meters)
0
200
400
600
800
1000
1200
1400
1600
0
1
2
3
4
5
6
7
Along Track Distance (kilometers)
-20
-40
-60
-80
-100
-120
-140
-160


Multi-Look Unfocused Radar Trace - Rough Topography
Unfocused
Multi-Look Unfocused
Power (dB)
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-500
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Depth (meters)


Multi-Look Unfocused Radargram - Smooth Topography
Depth (meters)
0
500
1000
1500
2000
2500
0
0.5
1
1.5
2
2.5
3
3.5
4
Along Track Distance (kilometers)
-20
-40
-60
-80
-100
-120
-140
-160


Multi-Look Unfocused Radar Trace - Smooth Topography
Unfocused
Multi-Look
Power (dB)
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-500
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Depth (meters)

Synthetic Aperture Processing

Advantages

Improves SNR
Improves SCR
Improves along-track resolution

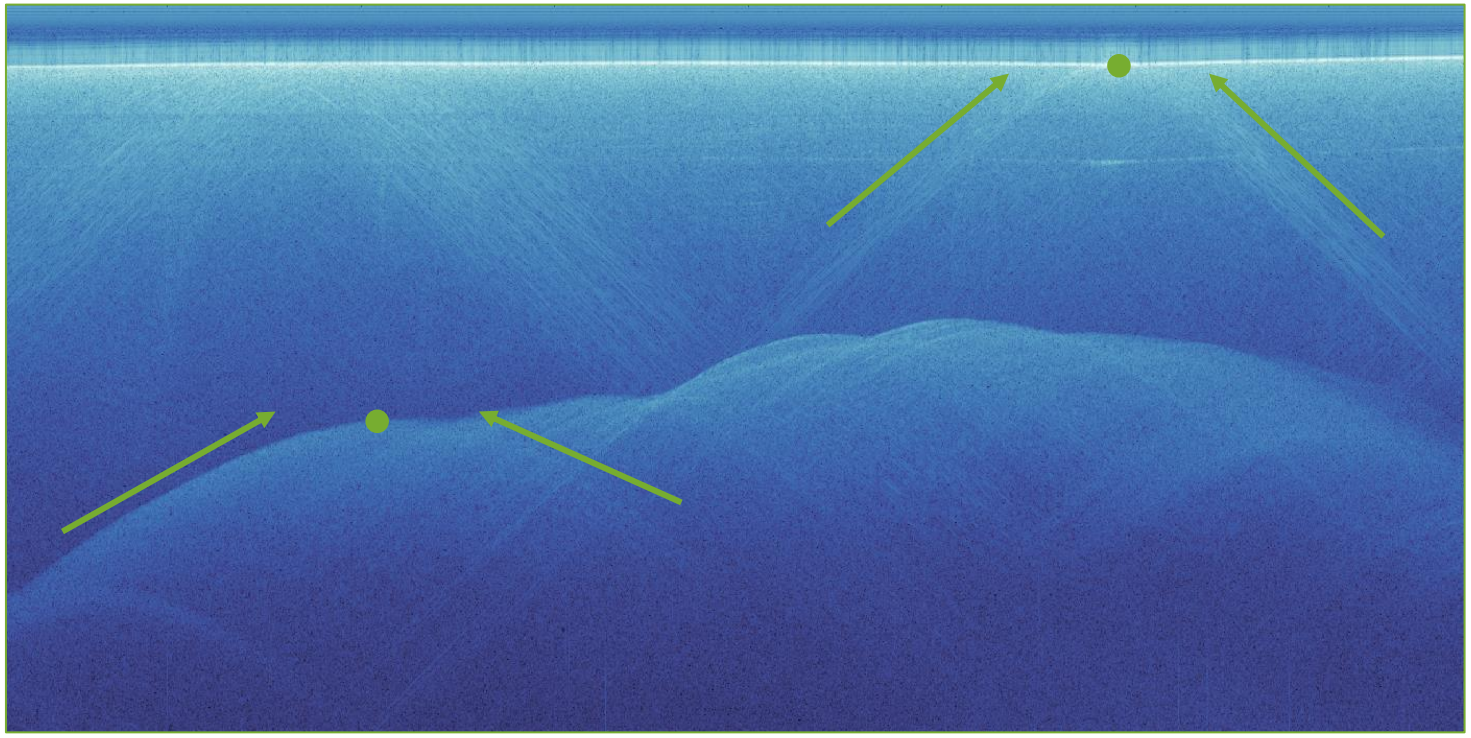
Rules of Thumb

Along-track resolution inversely proportional to aperture length.

SNR improvement proportional to aperture length.

Processing usually includes motion compensation.

Migrate hyperbolae back to scattering center



Synthetic Aperture Processing

Advantages

Improves SNR
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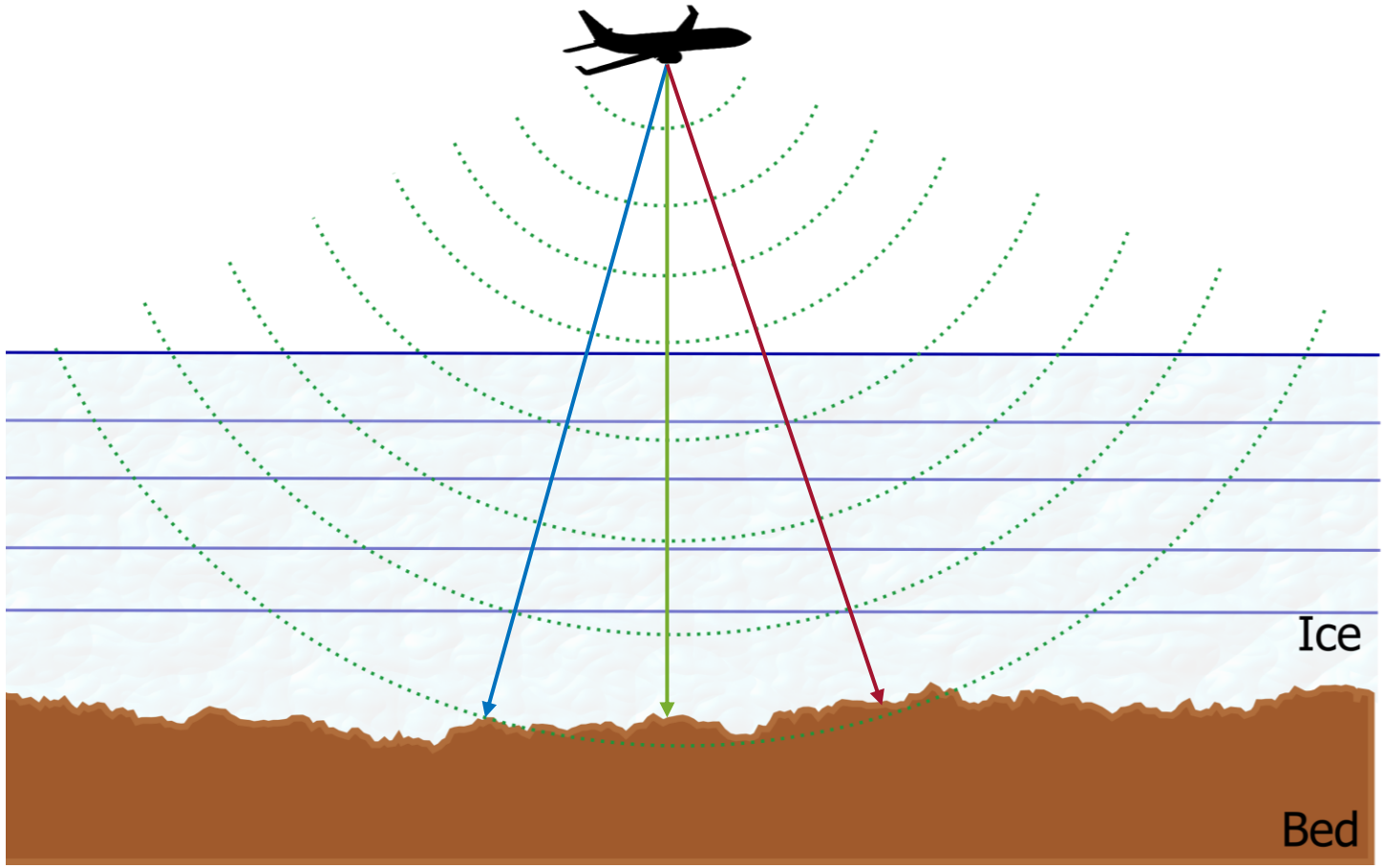
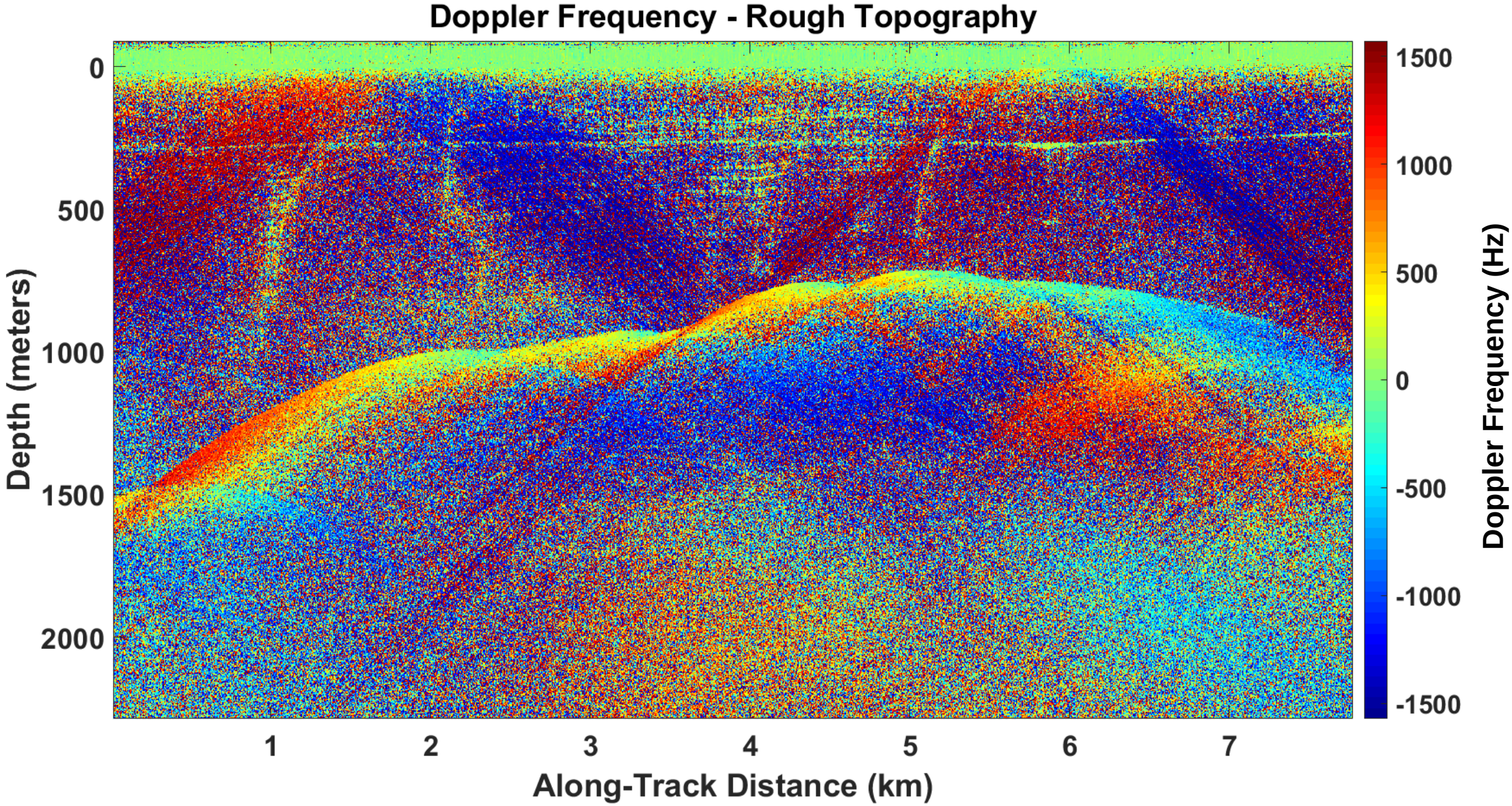
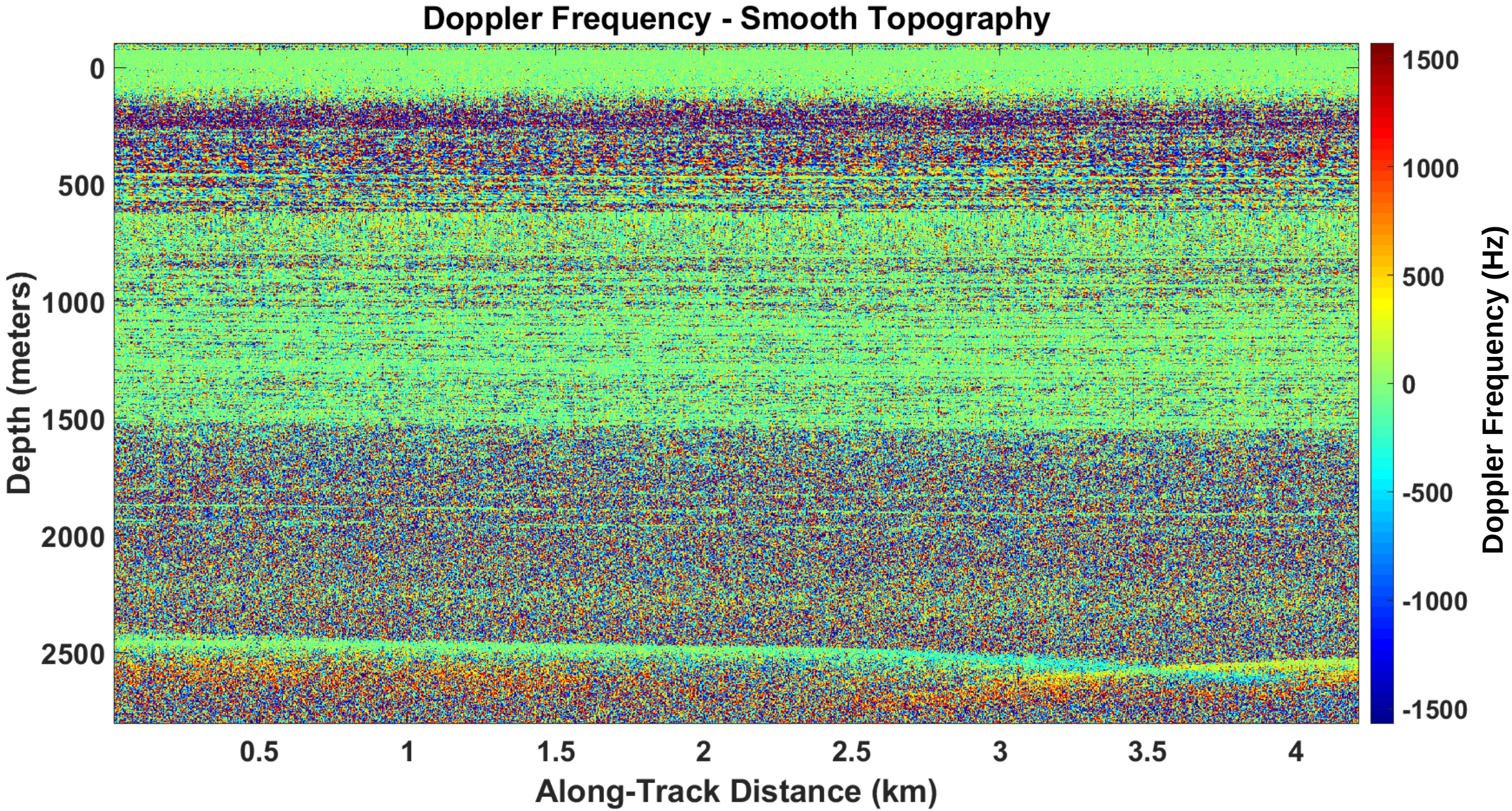
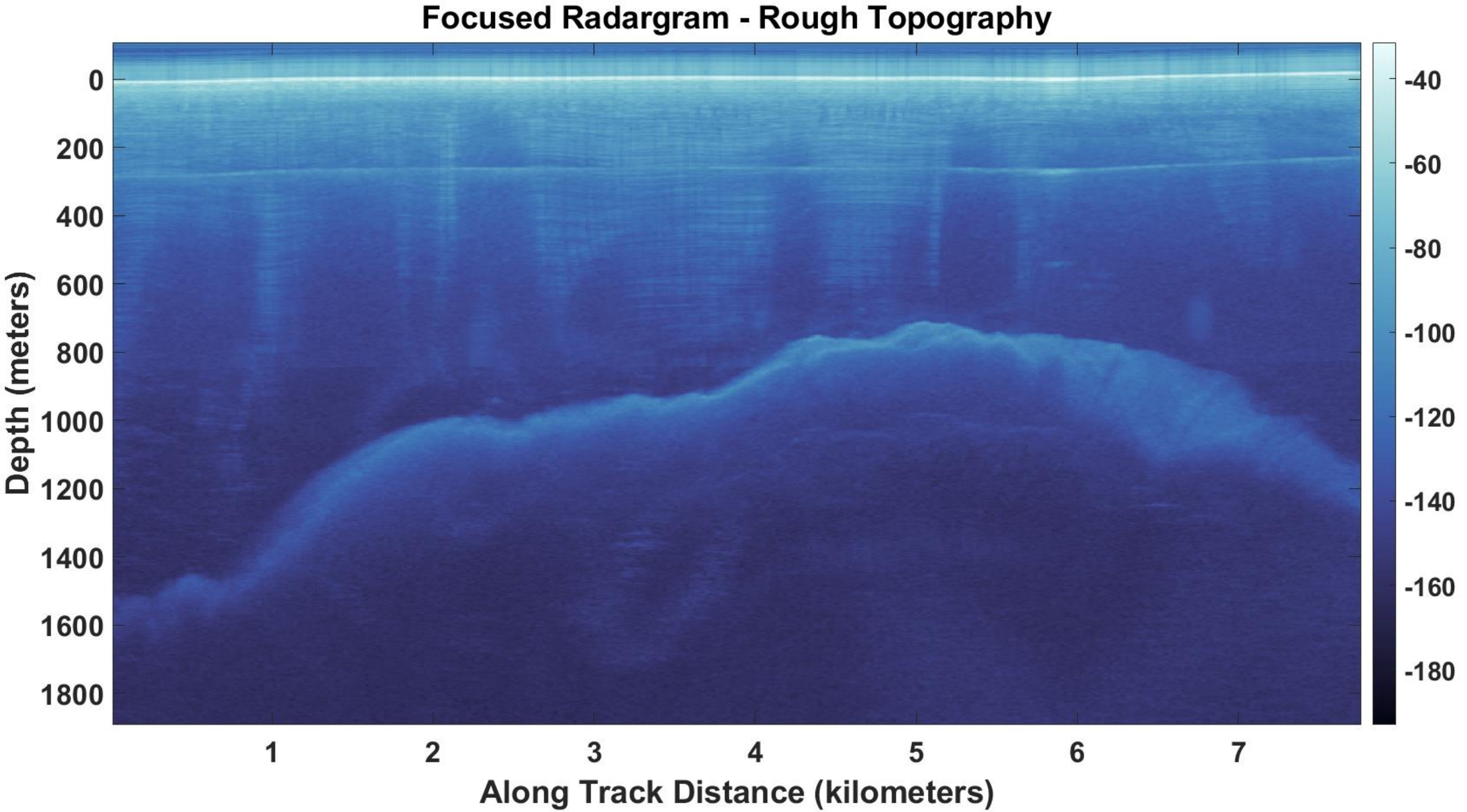
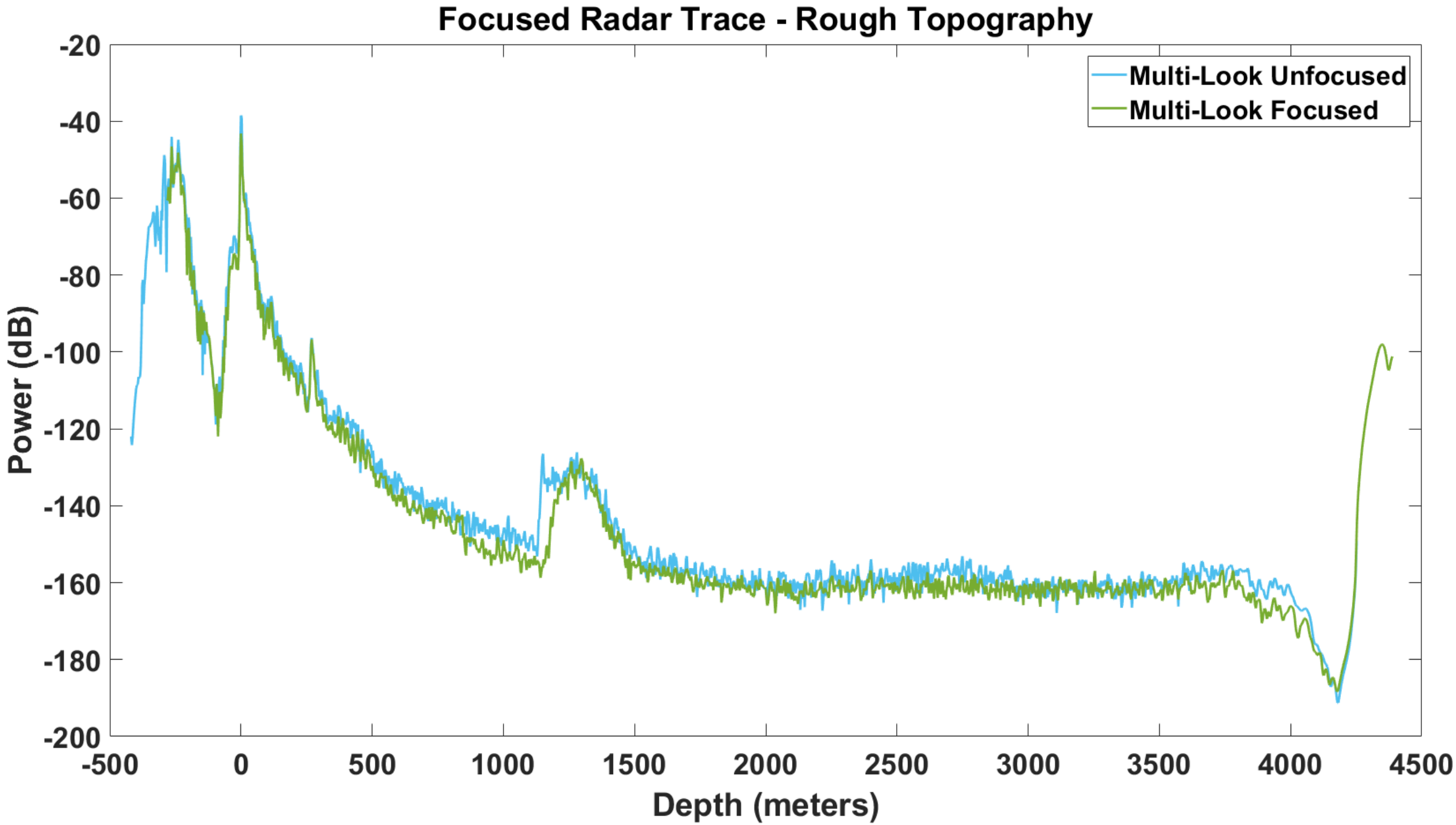
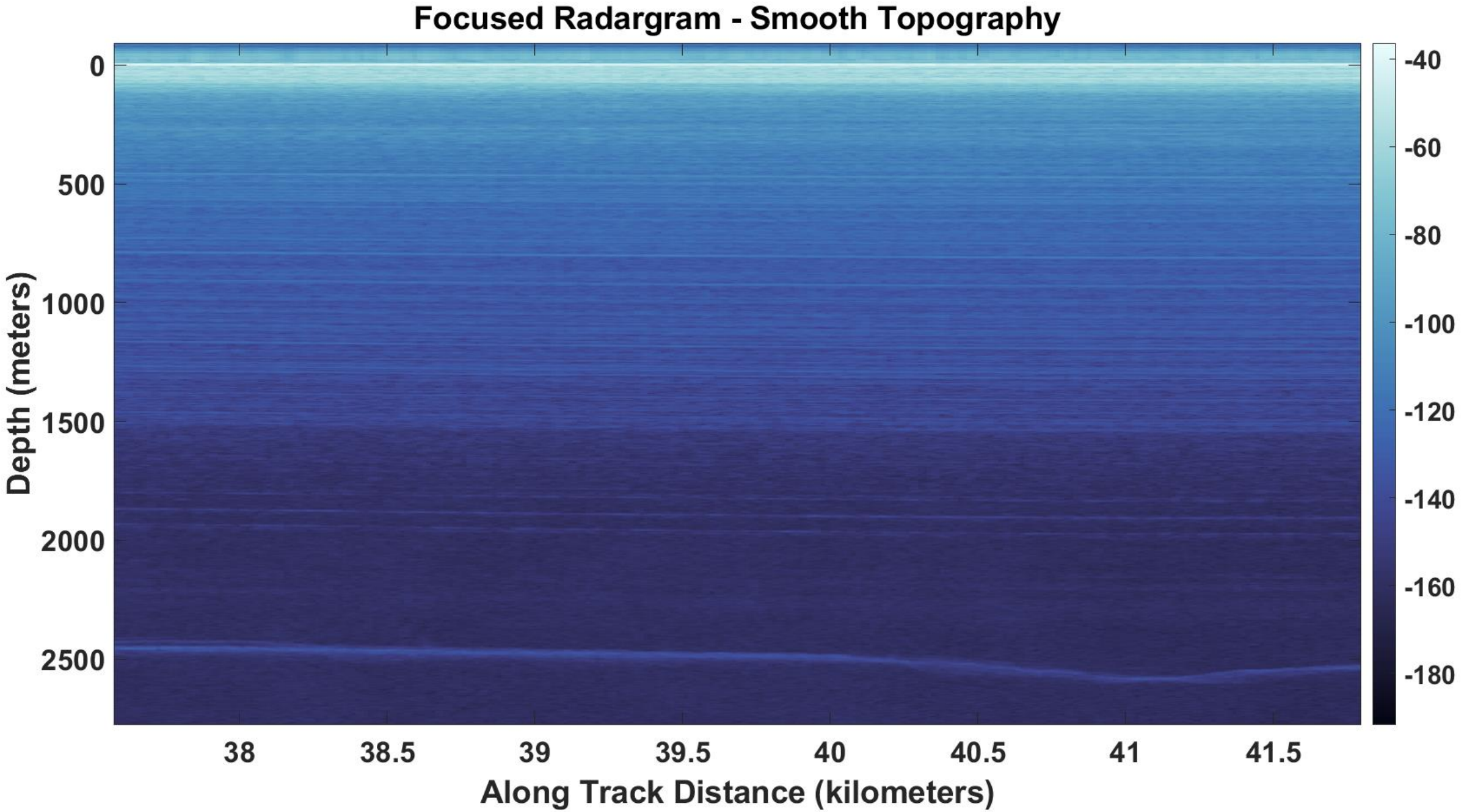


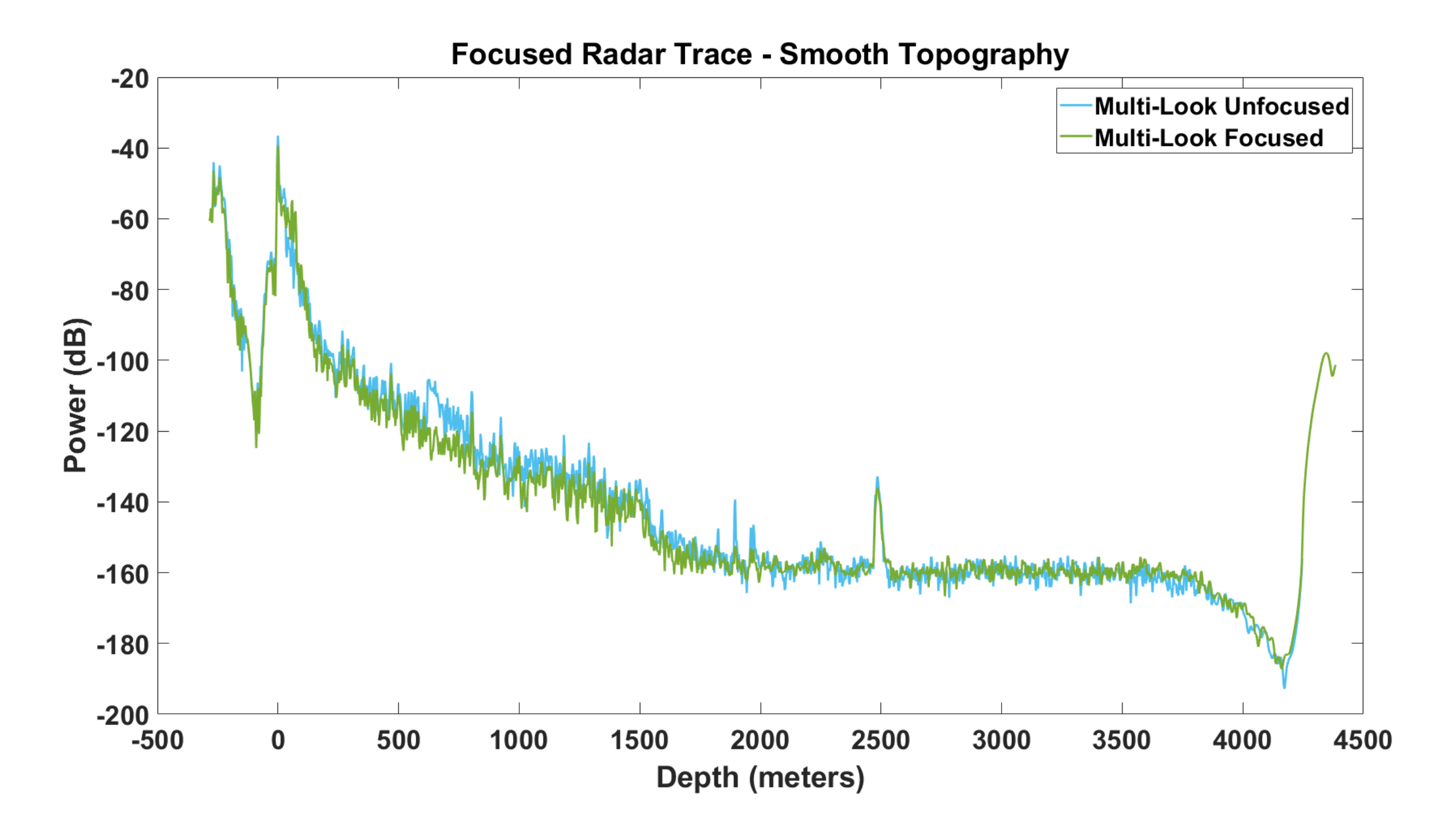

Doppler Frequency - Rough Topography
Depth (meters)
0
500
1000
1500
2000
1
2
3
4
5
6
7
Along-Track Distance (km)
1500
1000
500
0
-500
-1000
-1500
Doppler Frequency (Hz)

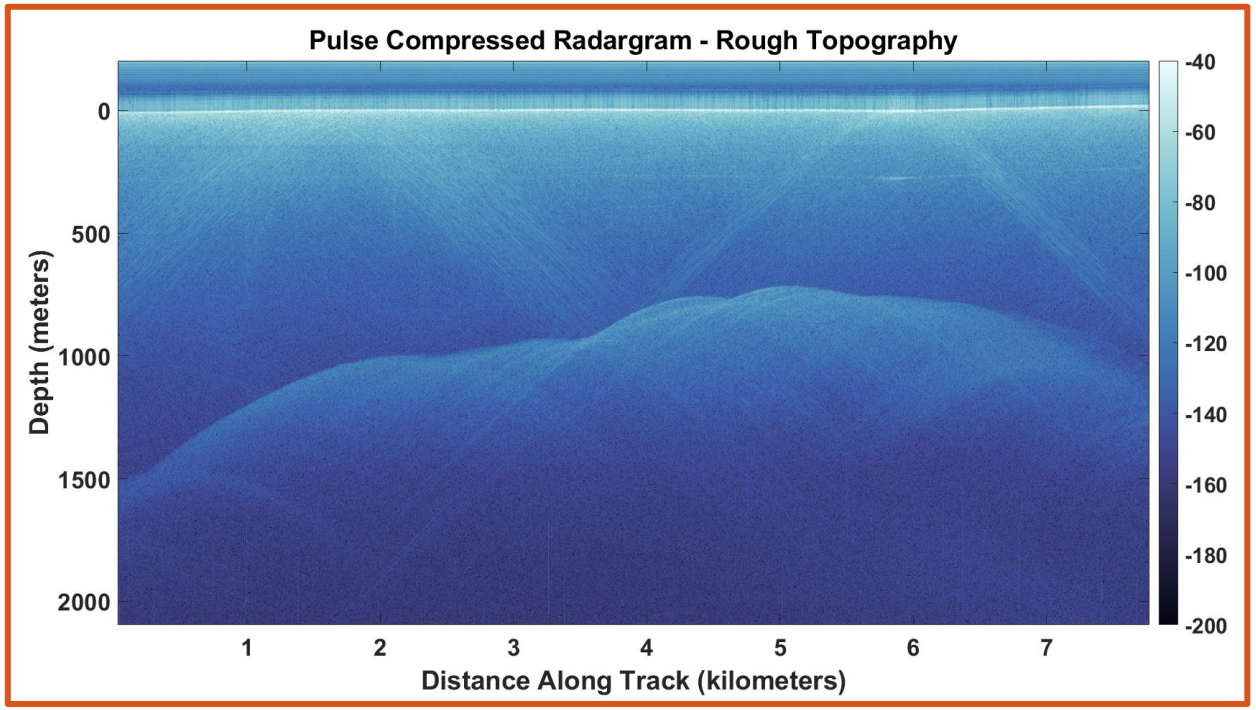

Doppler Frequency - Smooth Topography
Depth (meters)
0
500
1000
1500
2000
2500
0.5
1
1.5
2
2.5
3
3.5
4
Along-Track Distance (km)
1500
1000
500
0
-500
-1000
-1500
Doppler Frequency (Hz)

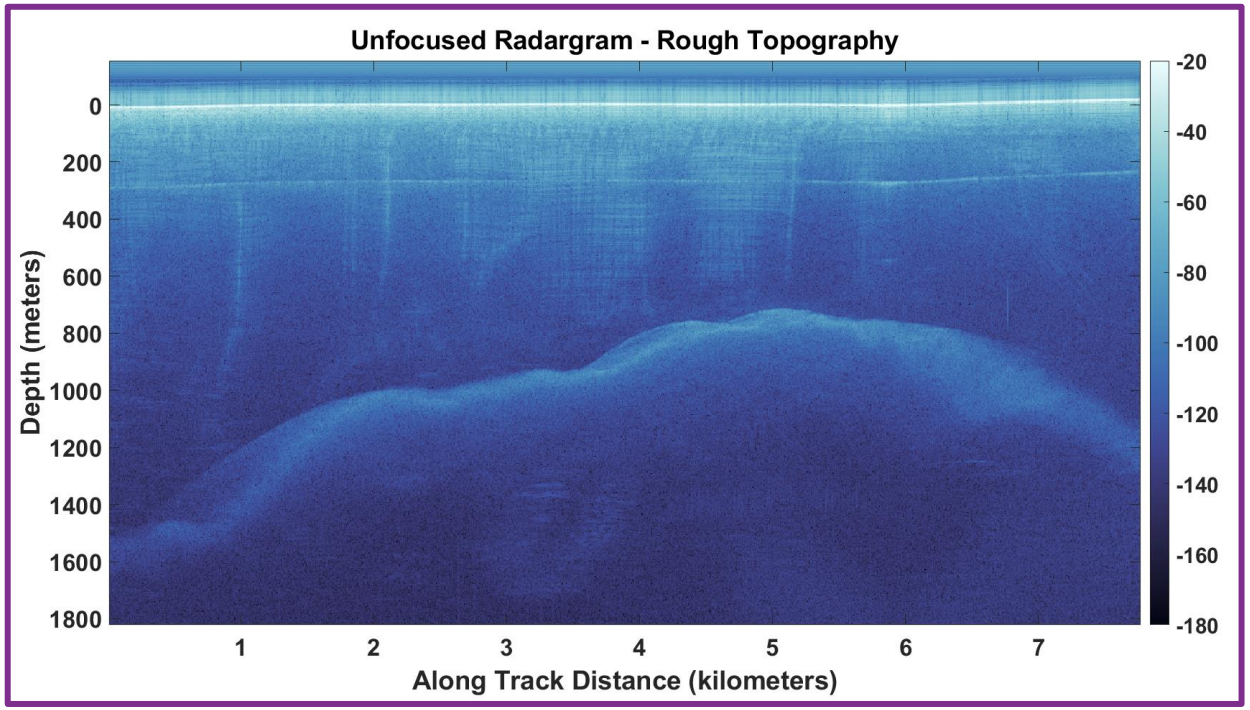

Focused Radargram - Rough Topography
Depth (meters)
0
200
400
600
800
1000
1200
1400
1600
1800
1
2
3
4
5
6
7
Along Track Distance (kilometers)
-40
-60
-80
-100
-120
-140
-160
-180

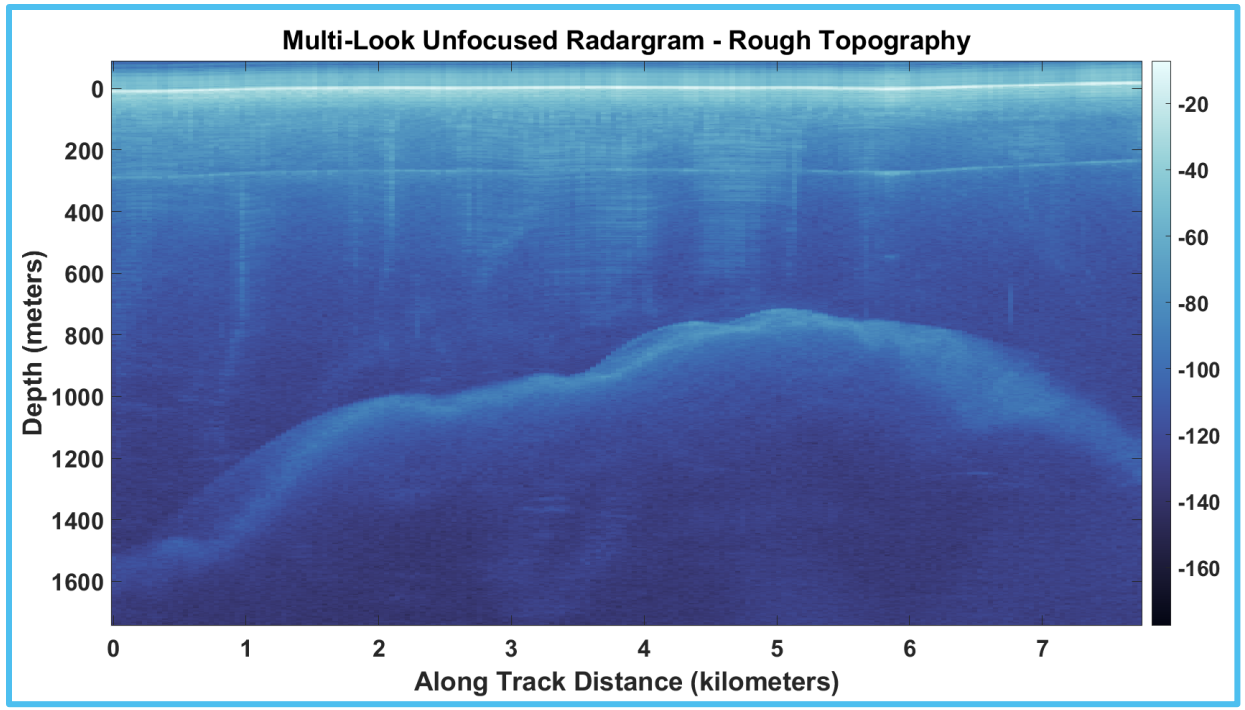

Focused Radar Trace - Rough Topography
Multi-Look Unfocused
Multi-Look Focused
Power (dB)
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-500
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Depth (meters)

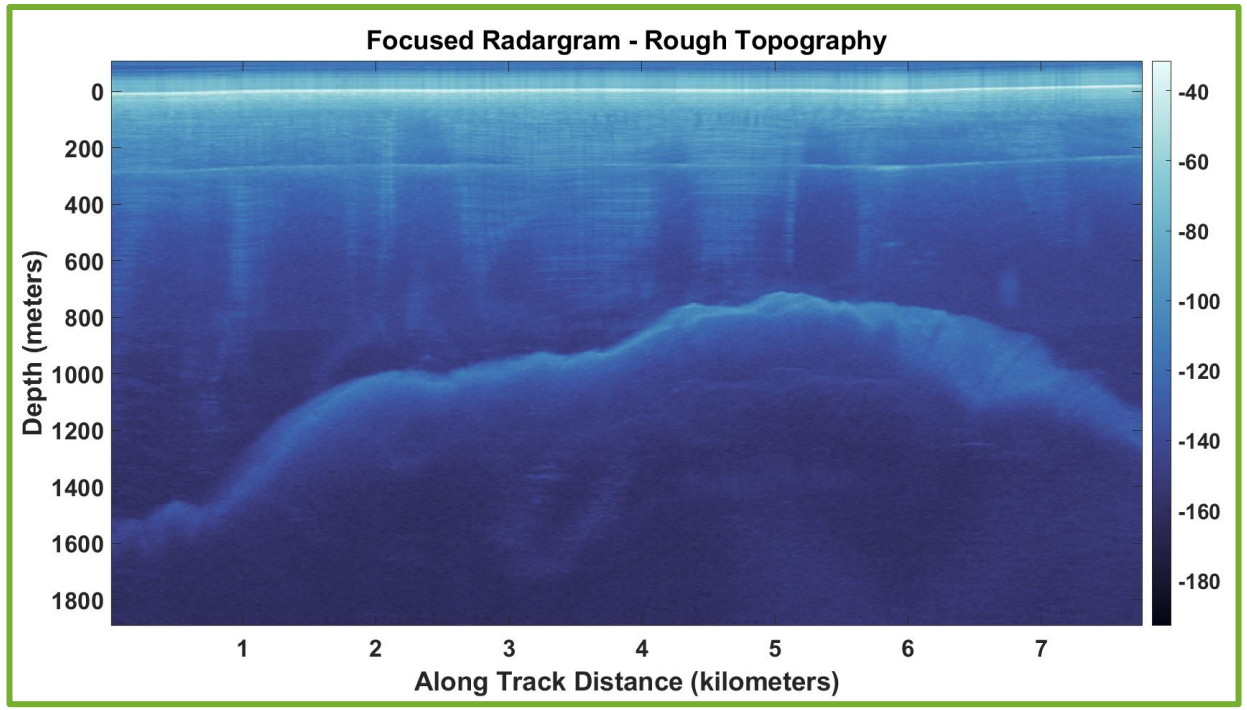

Focused Radargram - Smooth Topography
0
500
1000
1500
2000
2500
Depth (meters)
38
38.5
39
39.5
40
40.5
41
41.5
Along Track Distance (kilometers)
-40
-60
-80
-100
-120
-140
-160
-180

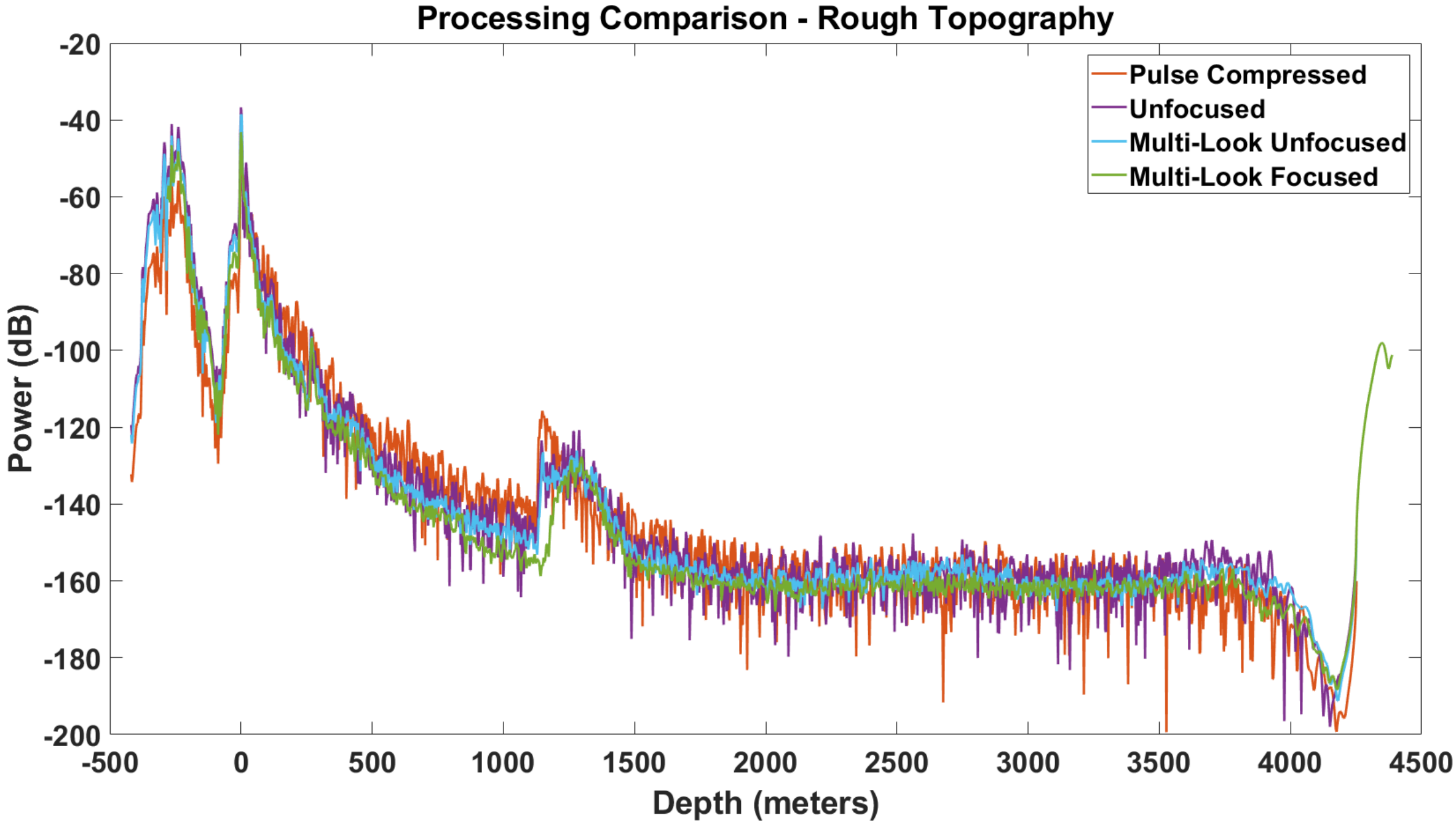

Focused Radar Trace - Smooth Topography
Multi-Look Unfocused
Multi-Look Focused
Power (dB)
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-500
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Depth (meters)

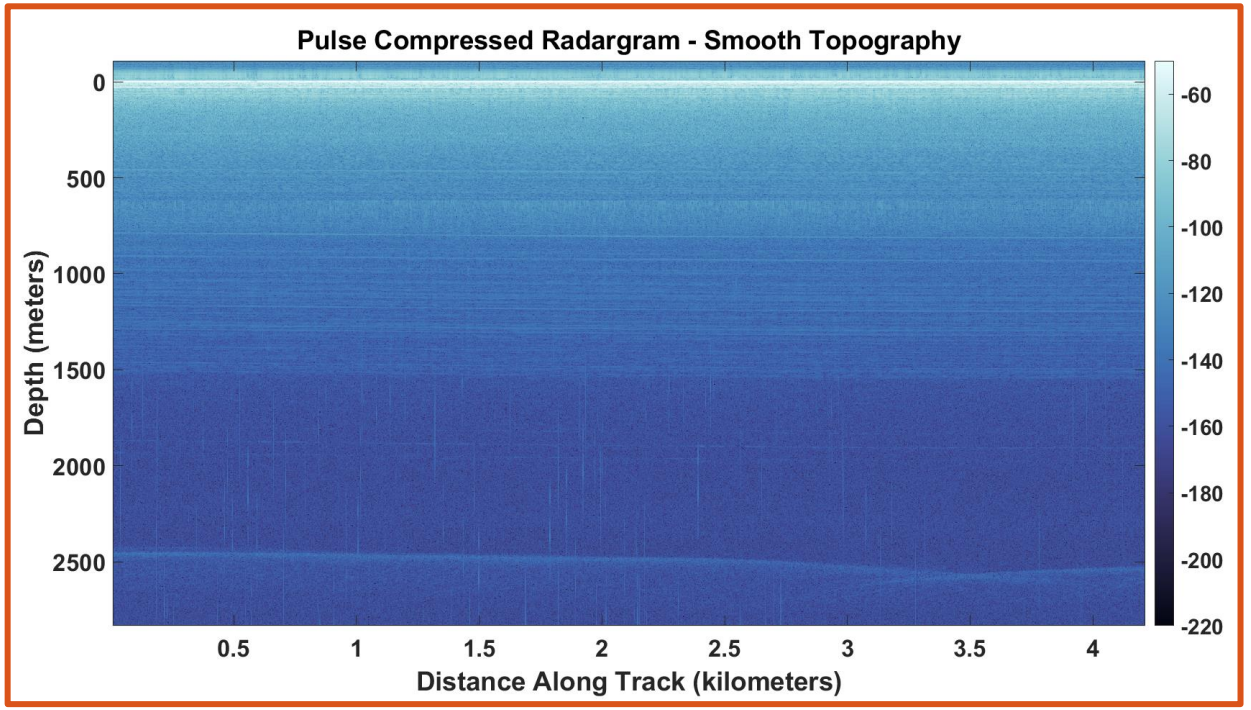

Pulse Compressed Radargram - Rough Topography
Depth (meters)
0
500
1000
1500
2000
1
2
3
4
5
6
7
Distance Along Track (kilometers)
-40
-60
-80
-100
-120
-140
-160
-180
-200

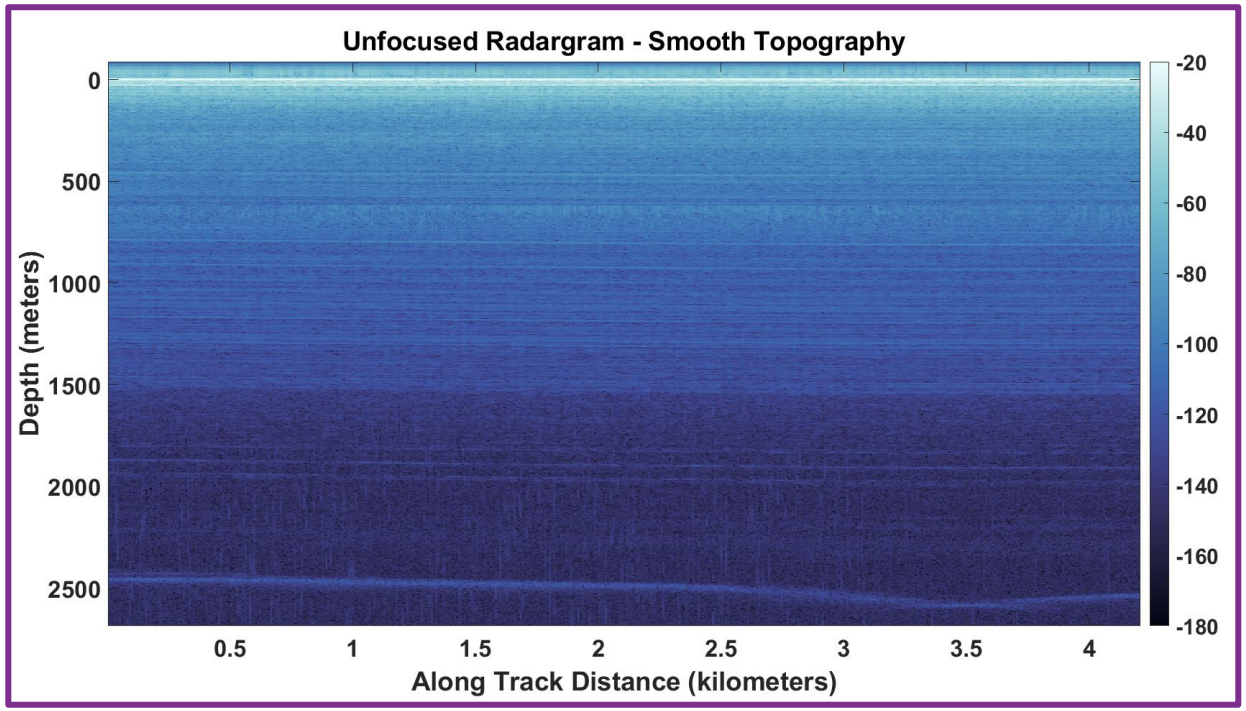

Unfocused Radargram - Rough Topography
Depth (meters)
0
200
400
600
800
1000
1200
1400
1600
1800
1
2
3
4
5
6
7
Along Track Distance (kilometers)
-20
-40
-60
-80
-100
-120
-140
-160
-180

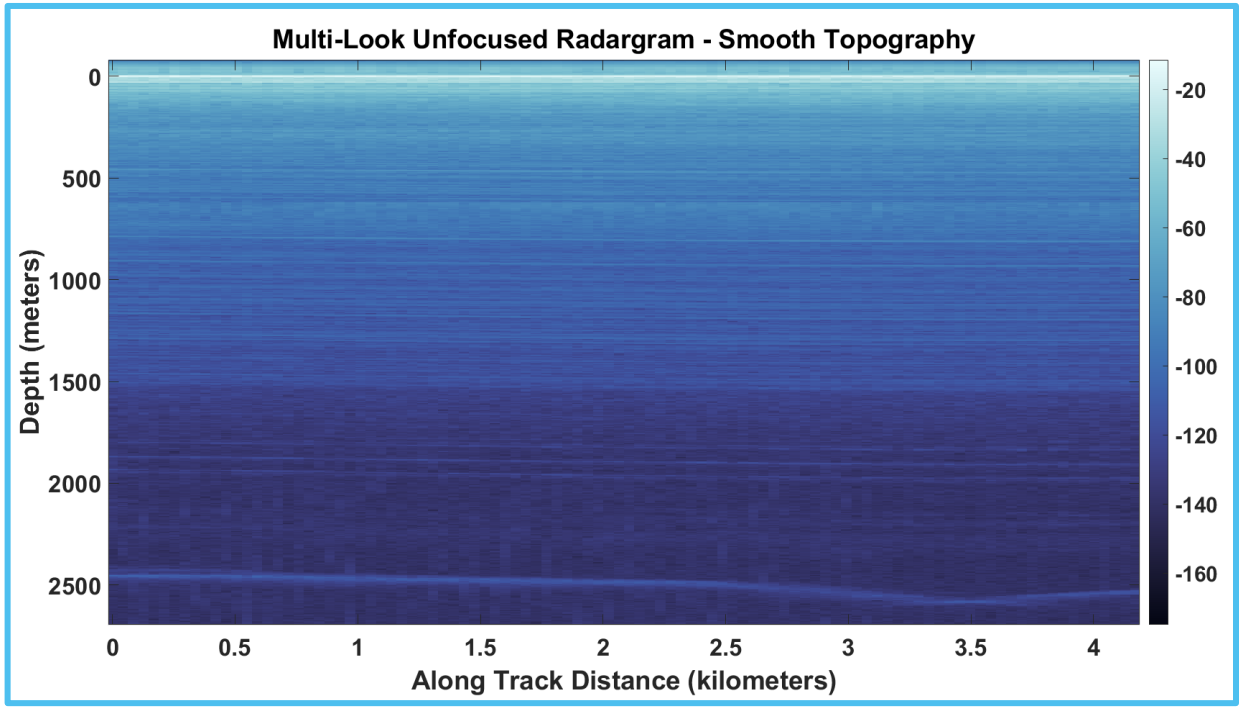

Multi-Look Unfocused Radargram - Rough Topography
Depth (meters)
0
200
400
600
800
1000
1200
1400
1600
0
1
2
3
4
5
6
7
Along Track Distance (kilometers)
-20
-40
-60
-80
-100
-120
-140
-160

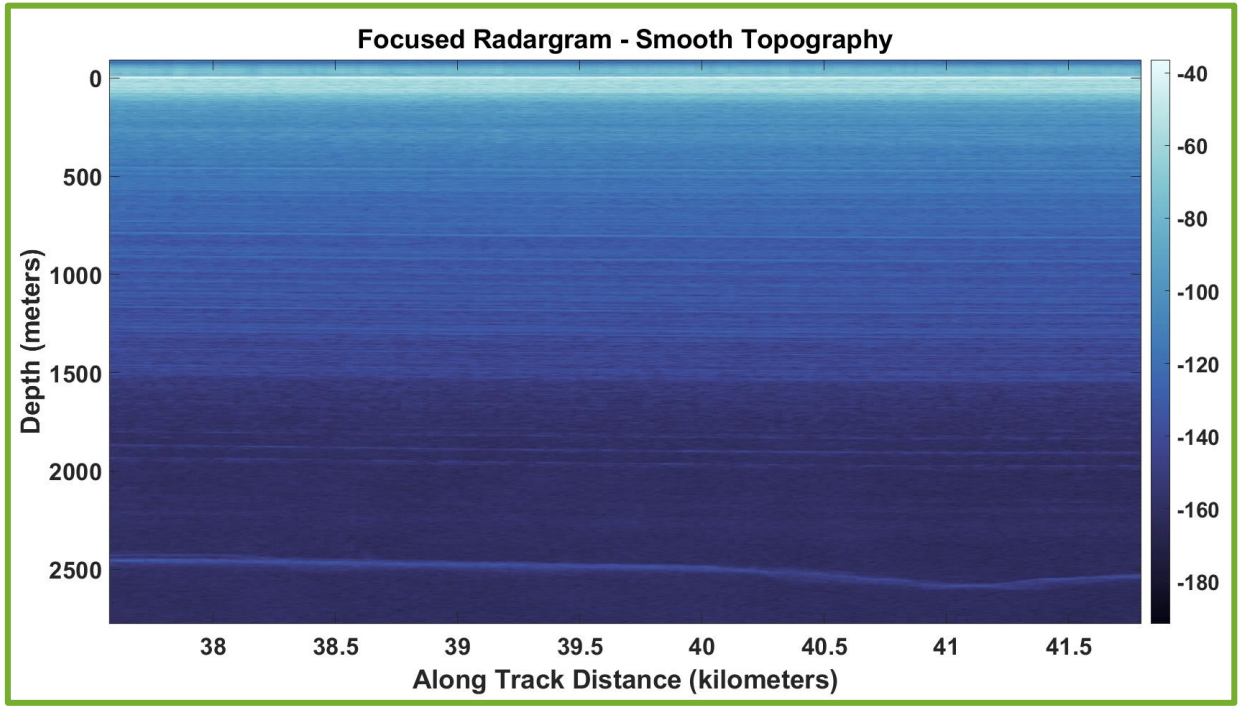

Focused Radargram - Rough Topography
Depth (meters)
0
200
400
600
800
1000
1200
1400
1600
1800
1
2
3
4
5
6
7
Along Track Distance (kilometers)
-40
-60
-80
-100
-120
-140
-160
-180

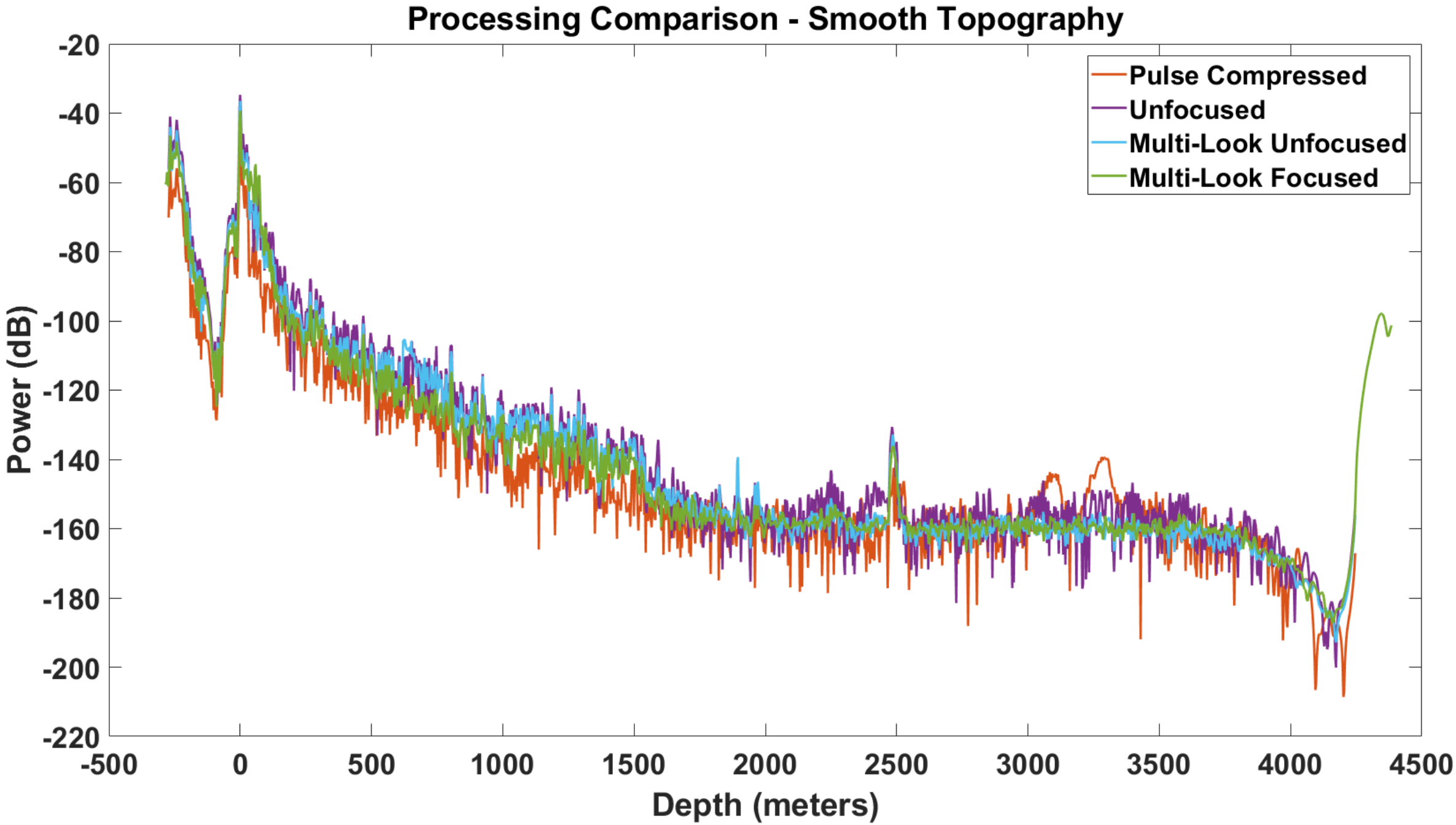

Processing Comparison - Rough Topography
Pulse Compressed
Unfocused
Multi-Look Unfocused
Multi-Look Focused
Power (dB)
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-500
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Depth (meters)


Pulse Compressed Radargram - Smooth Topography
Depth (meters)
0
500
1000
1500
2000
2500
0.5
1
1.5
2
2.5
3
3.5
4
Distance Along Track (kilometers)
-60
-80
-100
-120
-140
-160
-180
-200
-220


Unfocused Radargram - Smooth Topography
Depth (meters)
0
500
1000
1500
2000
2500
0.5
1
1.5
2
2.5
3
3.5
4
Along Track Distance (kilometers)
-20
-40
-60
-80
-100
-120
-140
-160
-180


Multi-Look Unfocused Radargram - Smooth Topography
Depth (meters)
0
500
1000
1500
2000
2500
0
0.5
1
1.5
2
2.5
3
3.5
4
Along Track Distance (kilometers)
-20
-40
-60
-80
-100
-120
-140
-160


Focused Radargram - Smooth Topography
Depth (meters)
0
500
1000
1500
2000
2500
38
38.5
39
39.5
40
40.5
41
41.5
Along Track Distance (kilometers)
-40
-60
-80
-100
-120
-140
-160
-180


Processing Comparison - Smooth Topography
Pulse Compressed
Unfocused
Multi-Look Unfocused
Multi-Look Focused
Power (dB)
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-500
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Depth (meters)

Some Typical Numbers for Radar Sounders

	MCoRDS	HiCARS	Accumulation Radar
Center Frequency	195 MHz	60 MHz	750 MHz
Wavelength (air/ice)	1.5 m / 0.86 m	5 m / 2.8 m	0.4 m / 0.22 m
Bandwidth	30 MHz	15 MHz	300 MHz
Pulse width	1 μs / 3 μs / 10 μs	1 μs	2.048 μs
PRF	12 kHz	6.4 kHz	50 kHz
Δr (air/ice)	7.6 m / 4.3 m	16.3 m / 9.2 m	0.76 m / 0.43 m
Sampling Rate (s)	111 MHz	50 MHz	1.6 GHz
r_f (surface/1000 m depth)	19.4 m / 28.2 m	35.4 m / 51.5 m	10 m / 14.5 m
r_{pl} (surface/1000 m depth)	87.2 m / 127 m	127.7 m / 186 m	27.6 m / 40.1 m
Coherent Stacks (onboard / post)	32 / 16	32 / 10	32 / 32
Incoherent Stacks	11 (moving average)	5	11 (moving average)
Δx_{at} (SAR processing)	~2.5 m	~10 m	~2.5 m
Trace spacing (m)	15 m	22 m	15 m