Keynote

2kR

SAR ALTIMETRY: PRECEDENT, PRESENT, & PROSPECTS

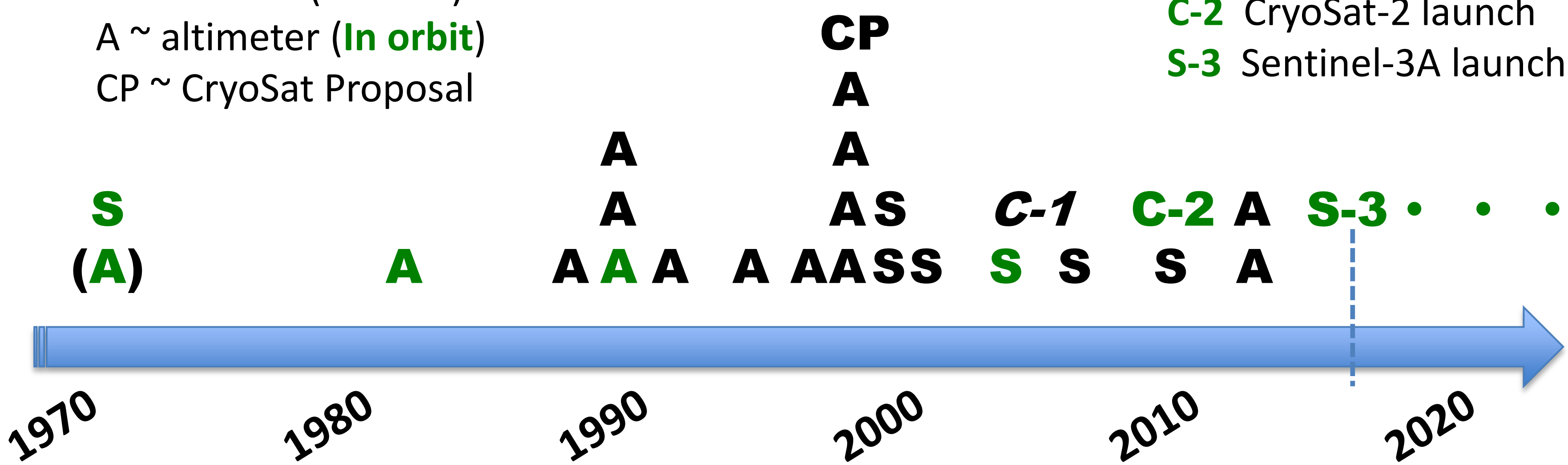
Fifty years following Apollo 17

R. Keith Raney
2kR, LLC

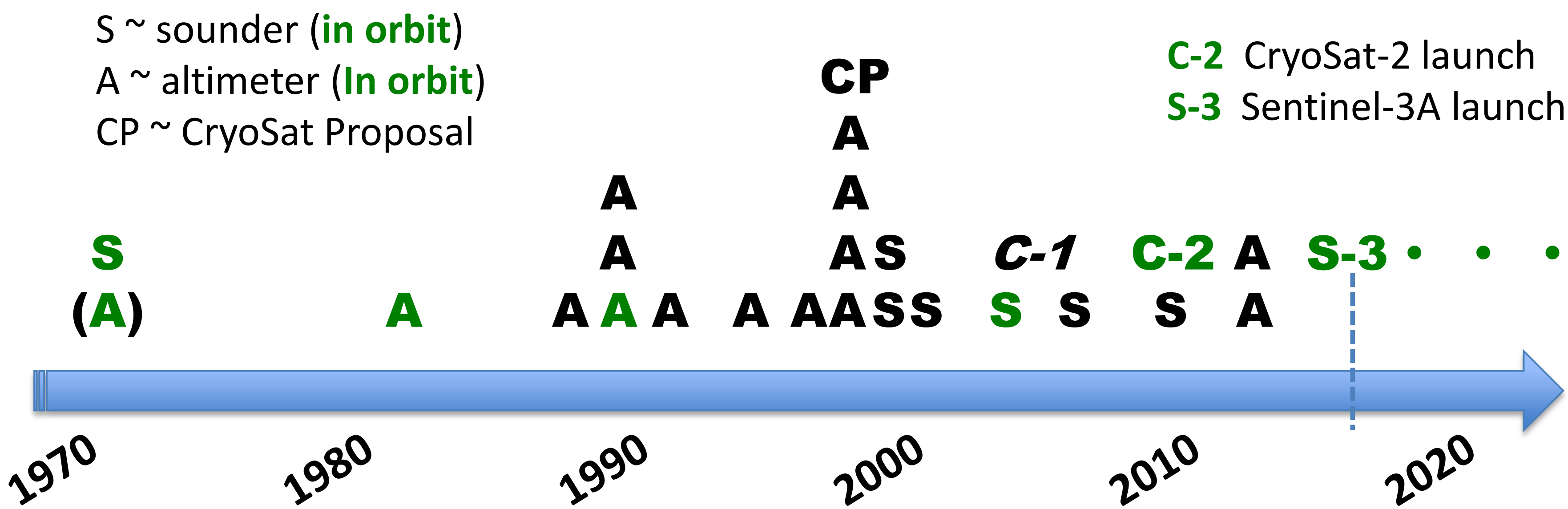
Fifty Years (*Selected milestones*)

S ~ sounder (**in orbit**)
A ~ altimeter (**In orbit**)
CP ~ CryoSat Proposal

C-2 CryoSat-2 launch
S-3 Sentinel-3A launch



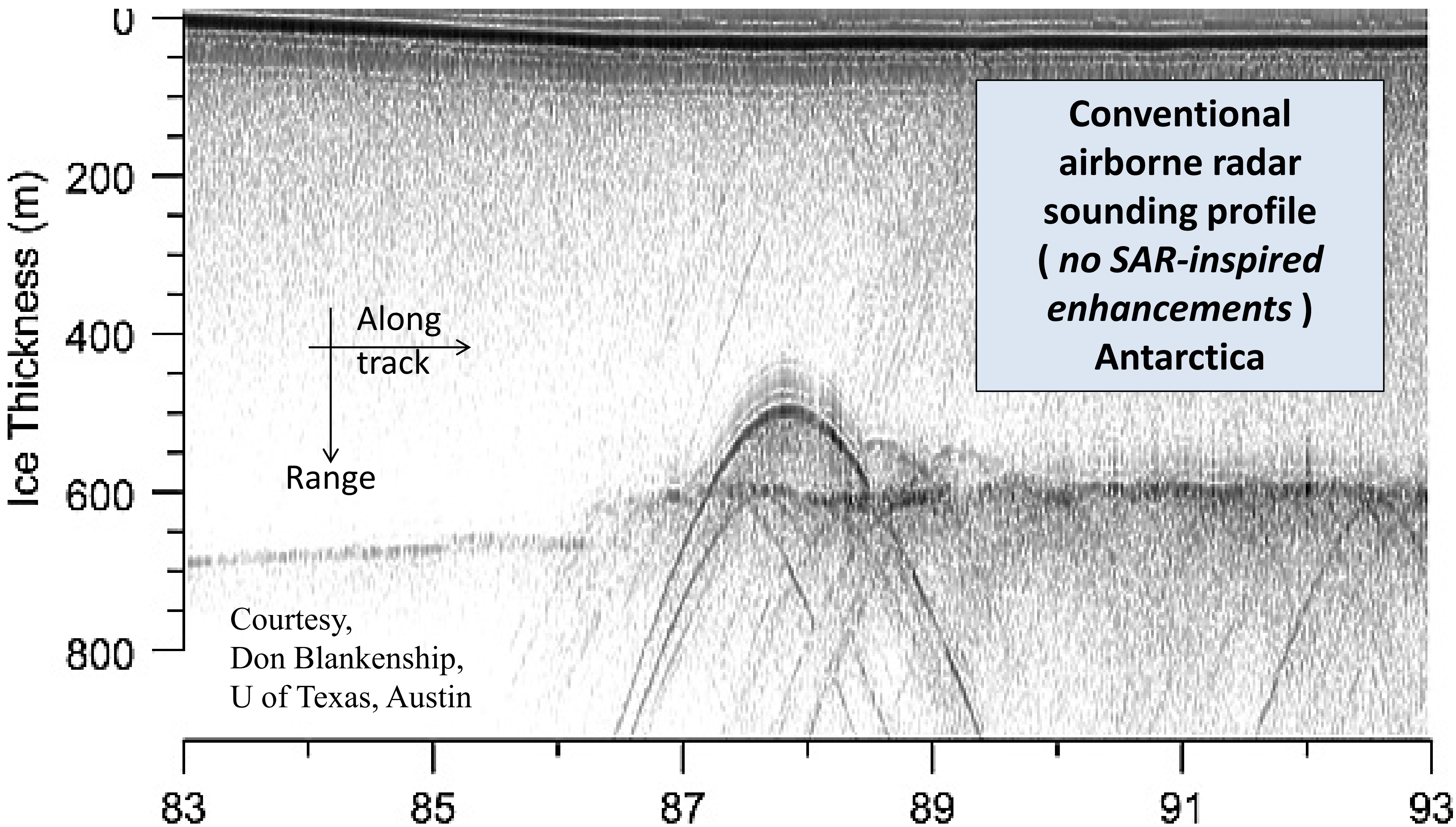
Fifty Years (*Selected milestones*)



***See** the annotated bibliography….*
"SAR Altimetry References (Selected)", *Program*, this meeting:
http://meetings.aviso.altimetry.fr/programs/complete-program.html

Names of note:
Aleksandrov, Barbarossa, Berry, Blankenship, Boy, Dall, Ford, Gommenginger, Griffiths, Jensen, Legarsky, Leuschen, Martin-Puig, Moore, Phalippou, Picardi, Porcello, Purseyyed, Raney, Rapley, Roca, Sorge, Wingham (and numerous others)

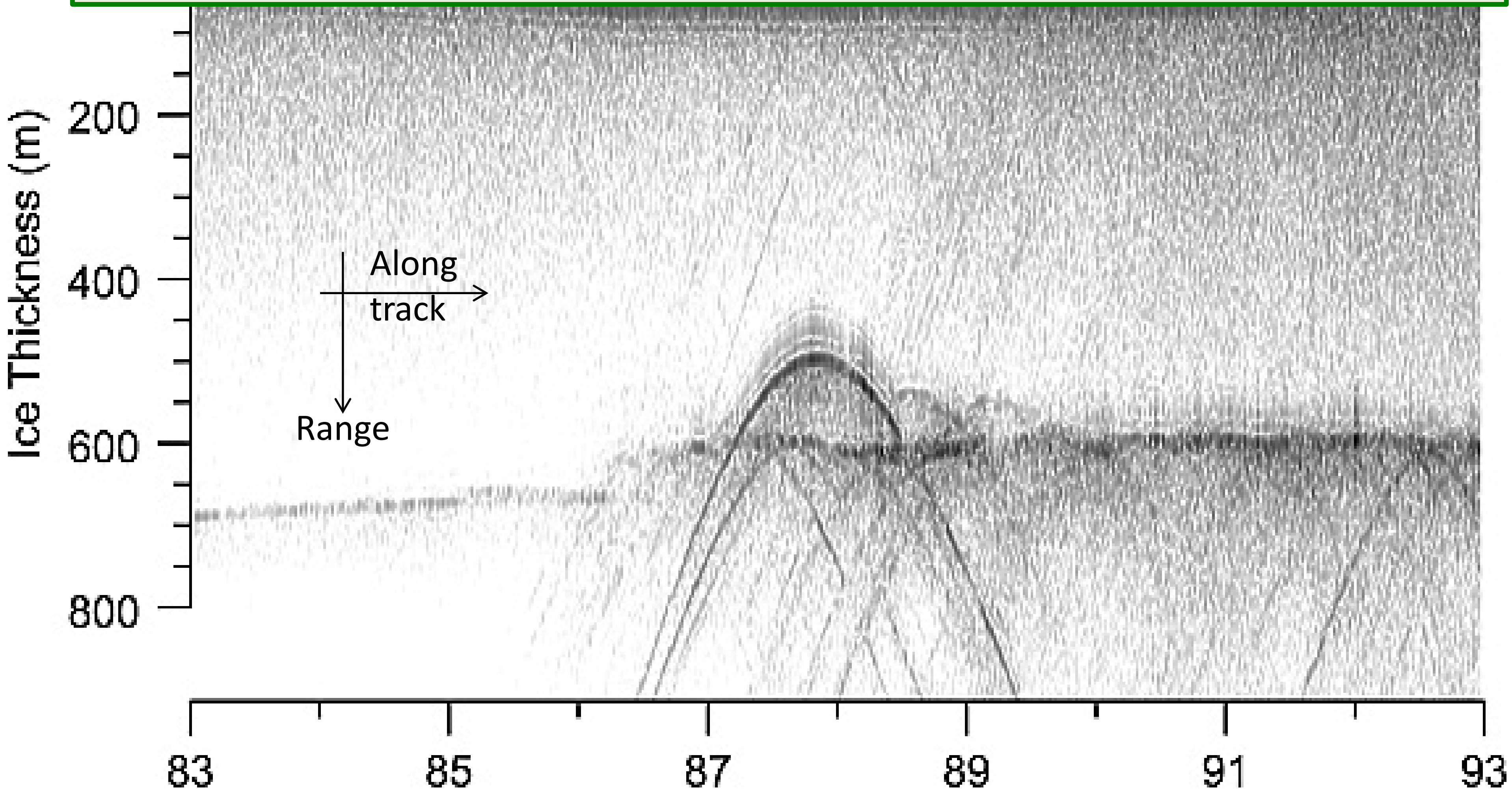
Radar Sounding . . .



Conventional airborne radar sounding profile (*no SAR-inspired enhancements*) Antarctica

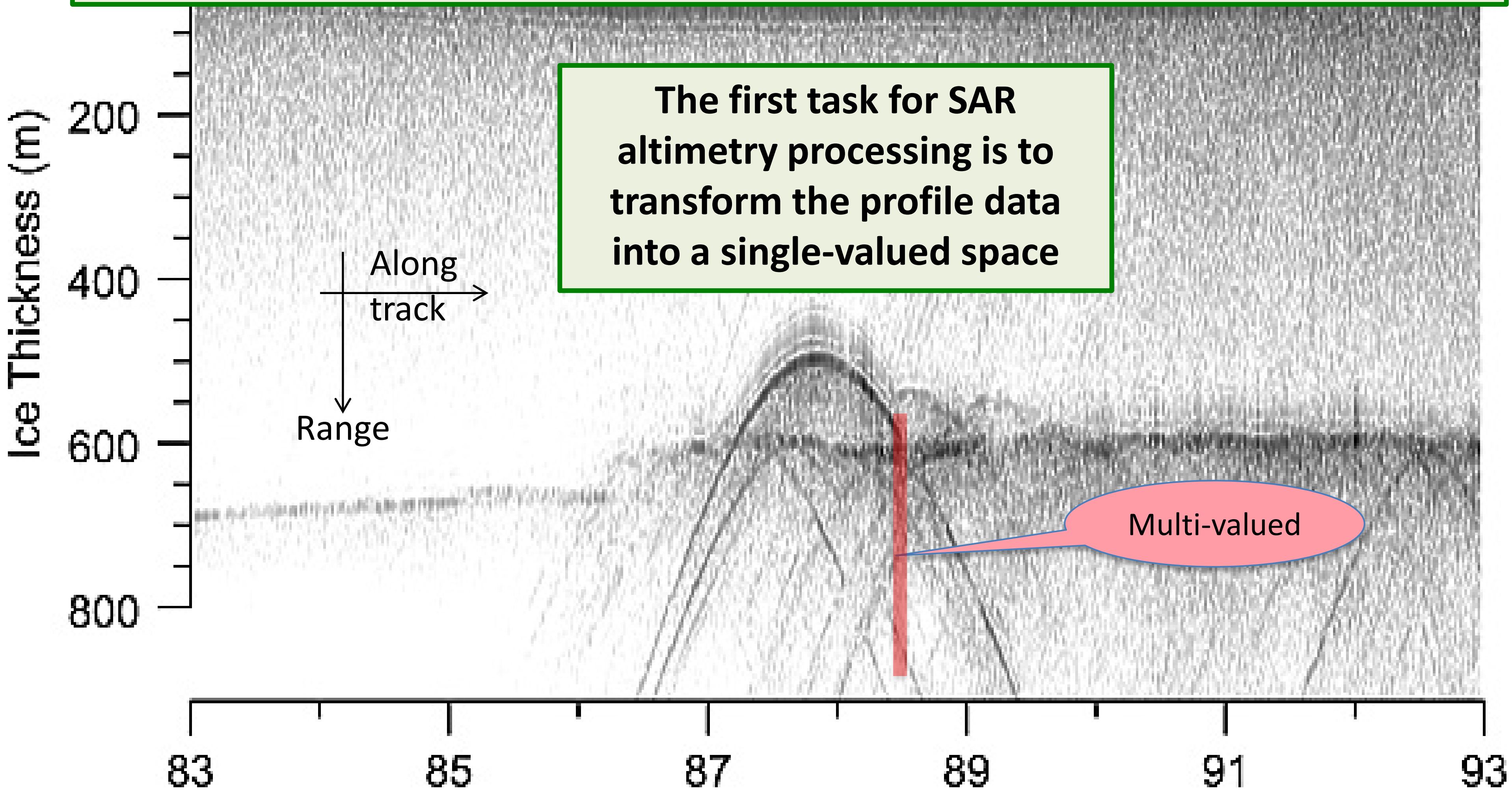
Radar Sounding . . .

***. . . is altimetry**, to a rough surface through a dense medium !*



Radar Sounding . . .

. . . *is altimetry*, *to a rough surface through a dense medium !*



Apollo 17

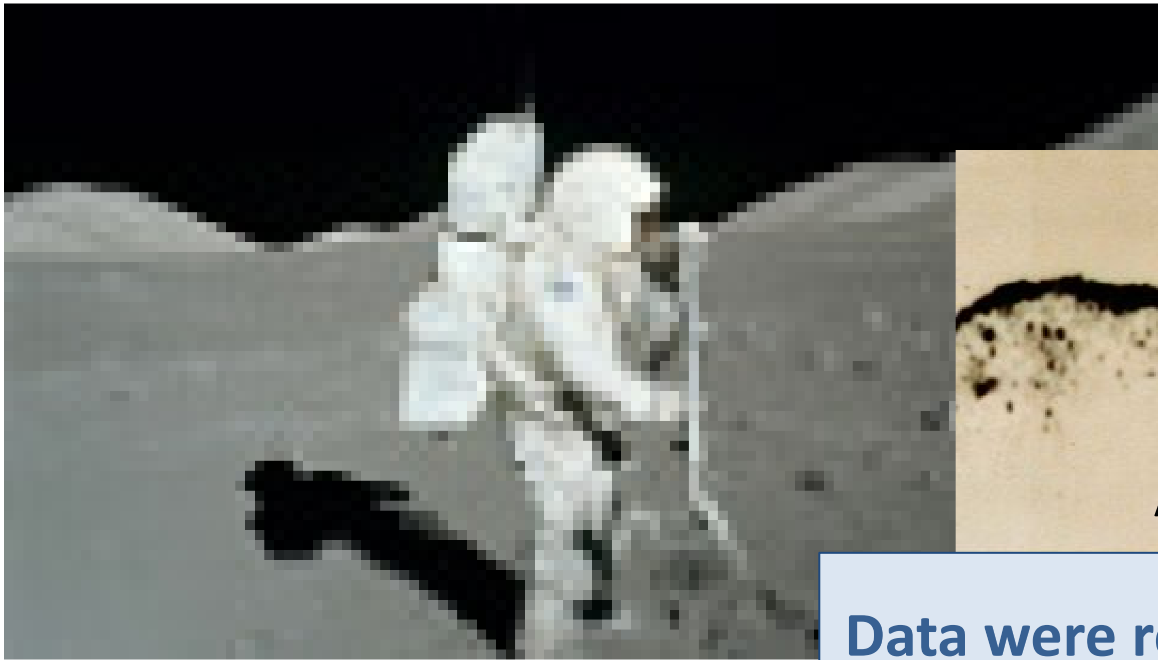
the 1972 Apollo Lunar Sounder Experiment (ALSE): focused SAR mode

A bit of field work for geologist Astronaut Harrison H. Schmitt

Data were recorded on film, returned to Earth, then processed optically.
The film canister had to be retrieved from the Service Module by EVA (Astronaut Ronald Evans)

Apollo 17

the 1972 Apollo Lunar Sounder Experiment (ALSE): focused SAR mode



A bit of field work for geologist Astronaut Harrison H. Schmitt

ALSE profile of Aitken Basin

Data were recorded on film, returned to Earth, then processed optically.
The film canister had to be retrieved from the Service Module by EVA (Astronaut Ronald Evans)

Apollo 17

the 1972 Apollo Lunar Sounder Experiment (ALSE): focused SAR mode

No hyperbolic signatures !

Excellent ! !

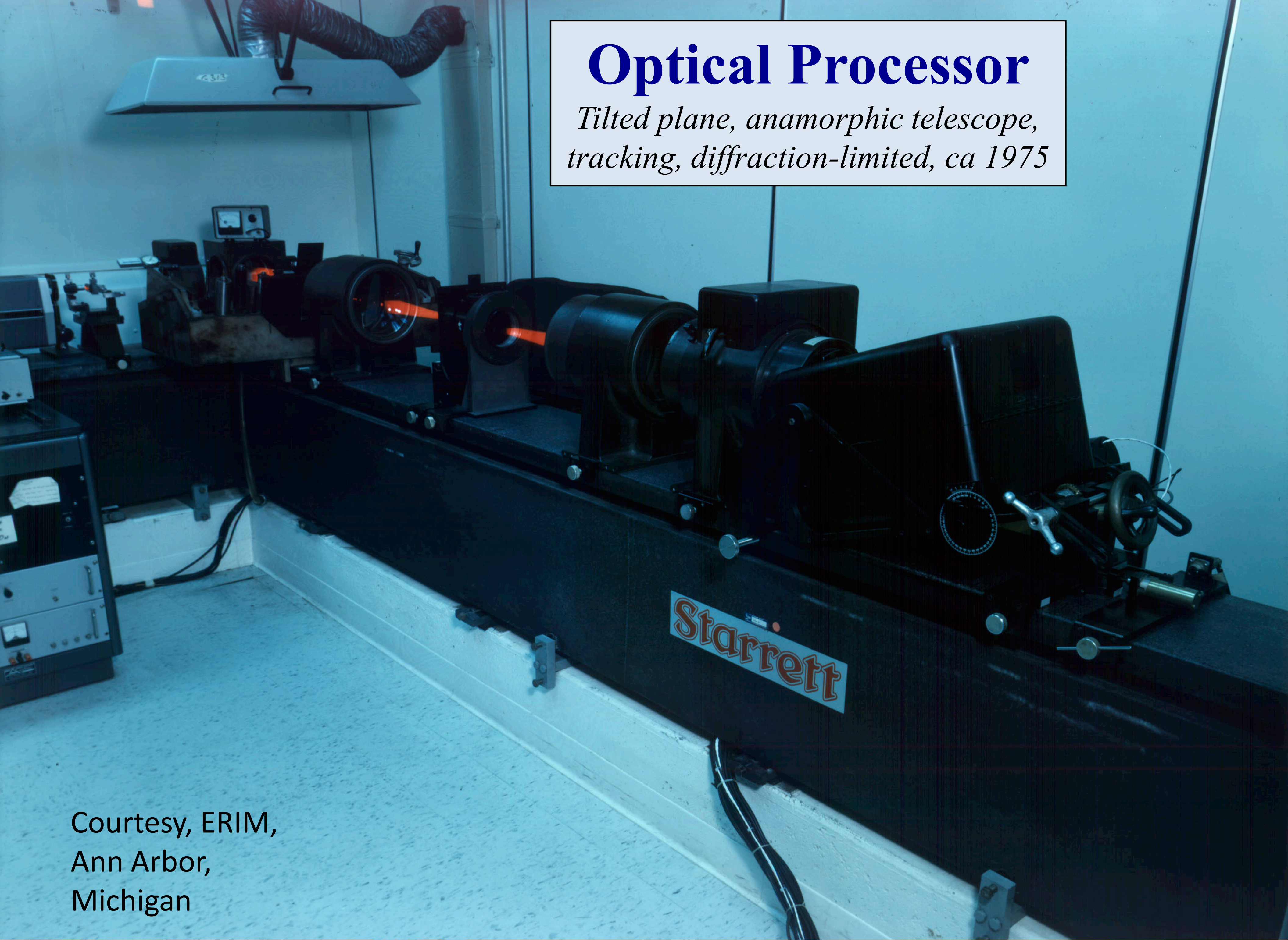
ALSE profile of Aitken Basin

A bit of field work for geologist Astronaut Harrison H. Schmitt

Data were recorded on film, returned to Earth, then processed optically.
The film canister had to be retrieved from the Service Module by EVA (Astronaut Ronald Evans)

Optical Processor

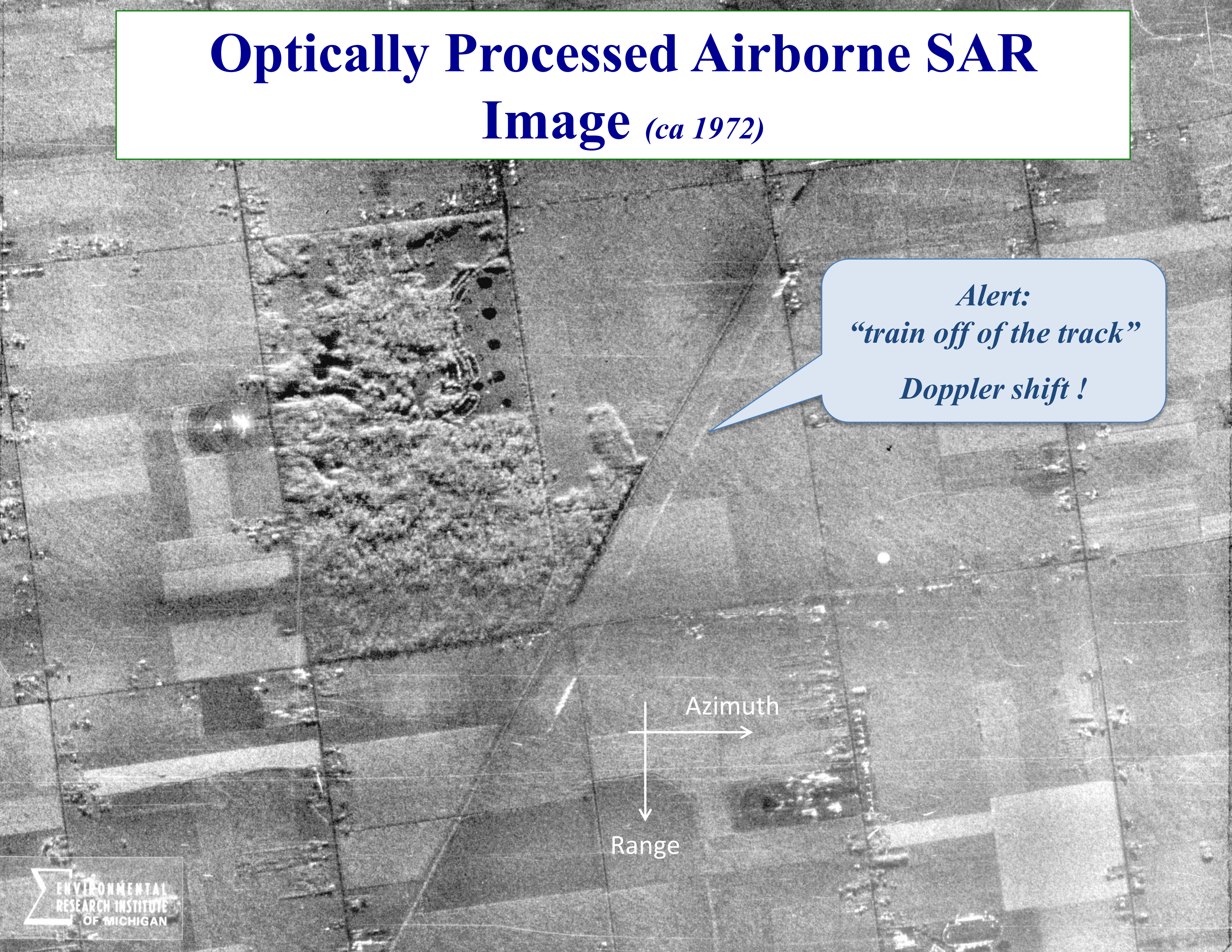
Tilted plane, anamorphic telescope, tracking, diffraction-limited, ca 1975

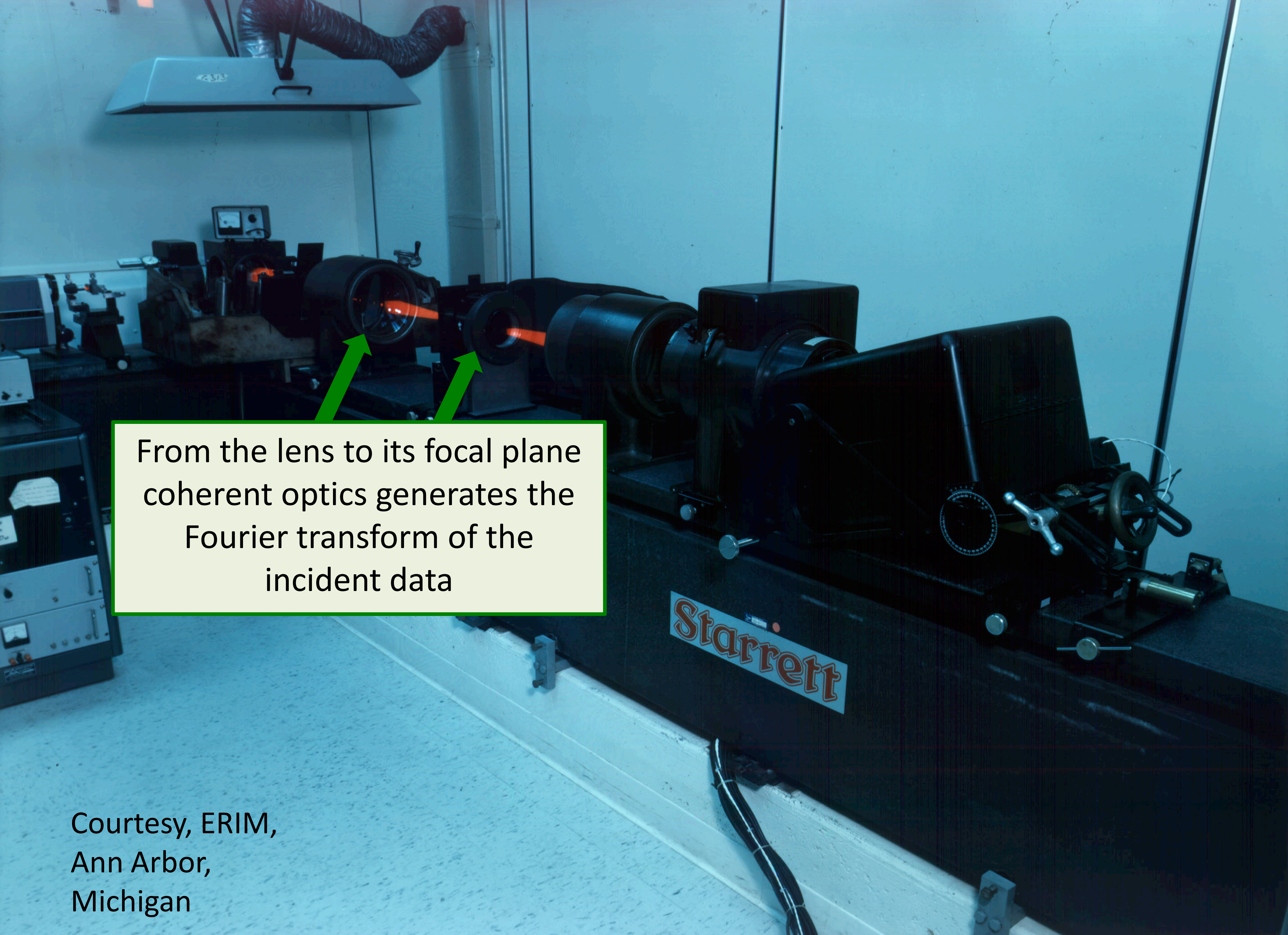


Courtesy, ERIM, Ann Arbor, Michigan

Optically Processed Airborne SAR Image *(ca 1972)*

Optically Processed Airborne SAR Image *(ca 1972)*

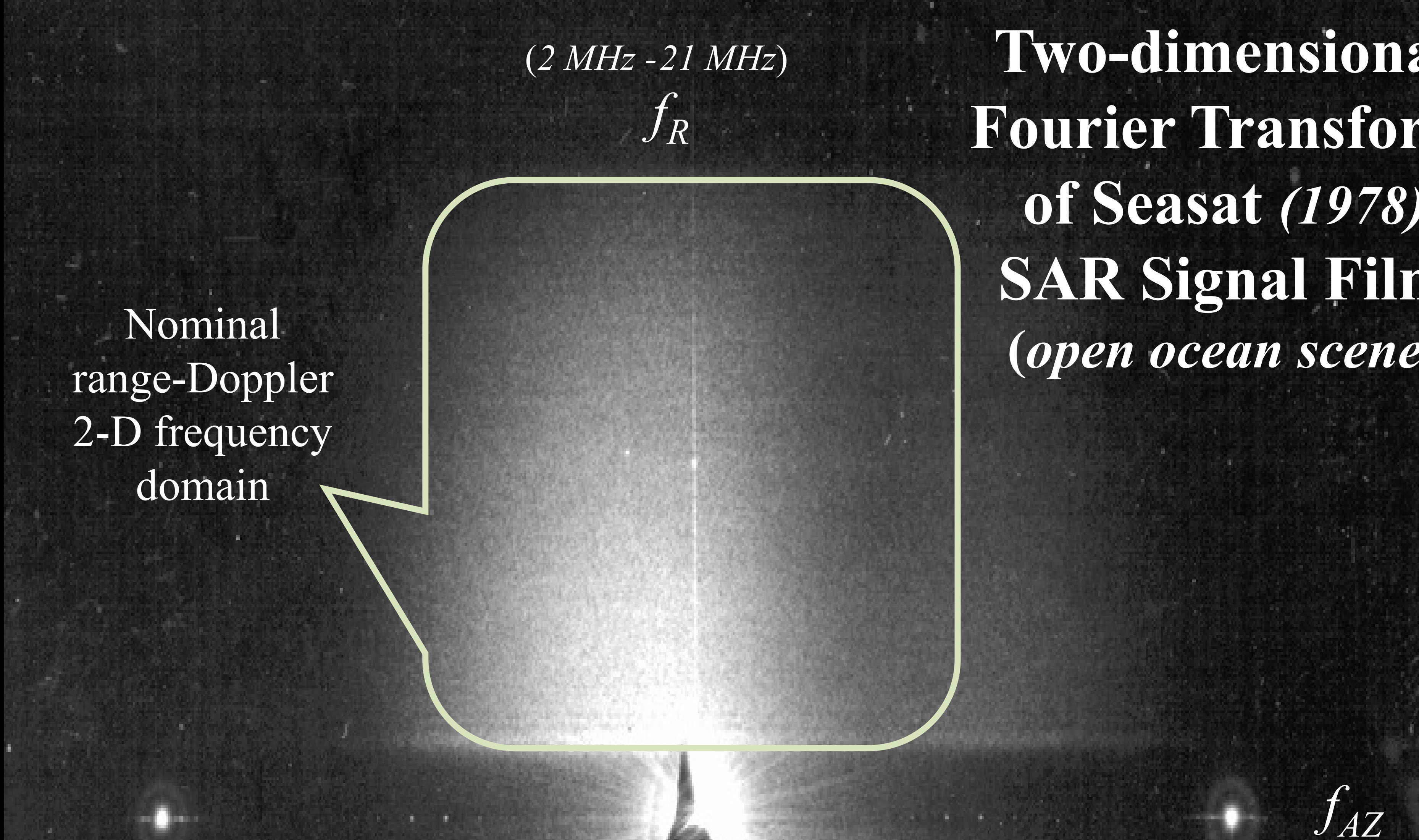




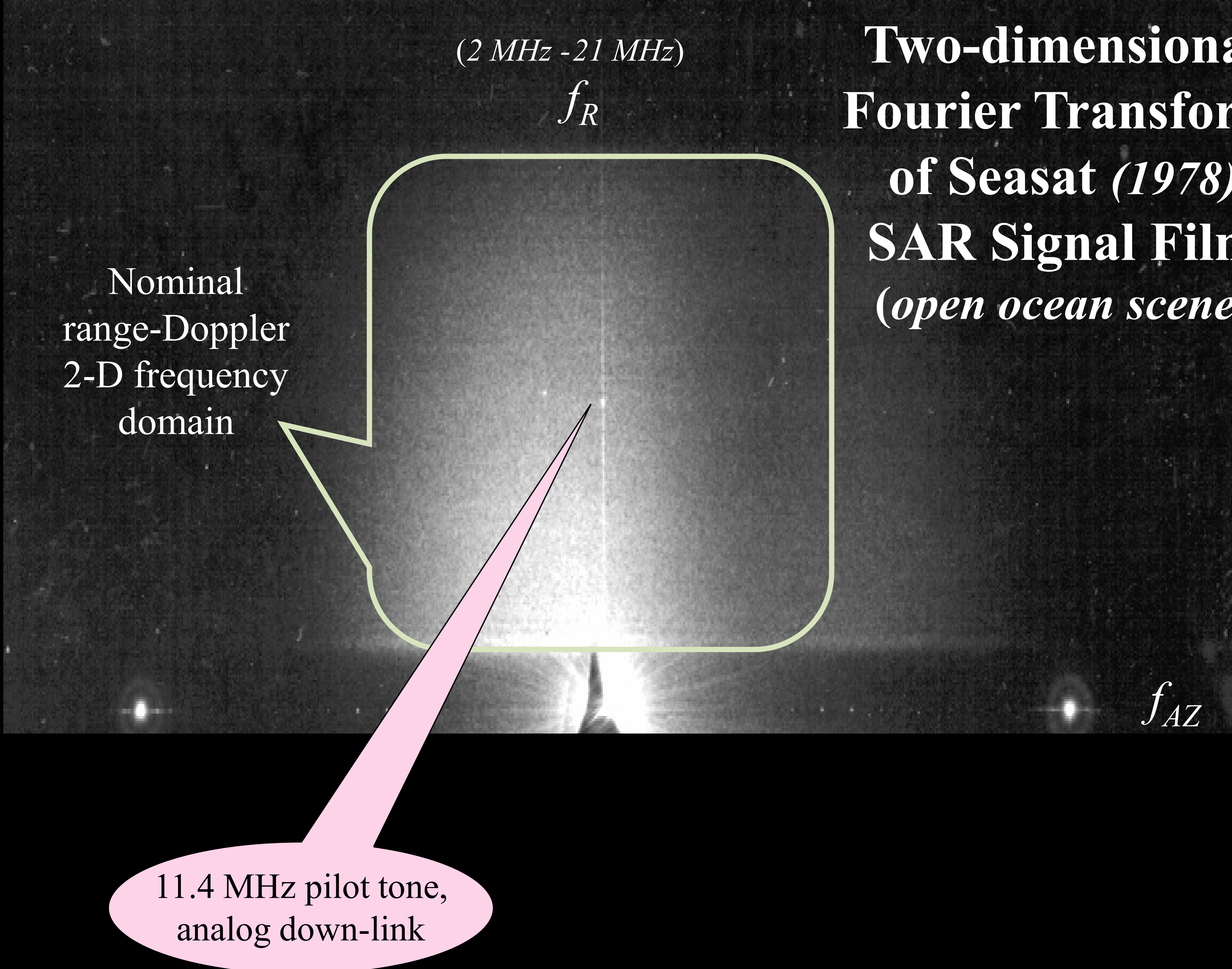
From the lens to its focal plane coherent optics generates the Fourier transform of the incident data

Courtesy, ERIM, Ann Arbor, Michigan

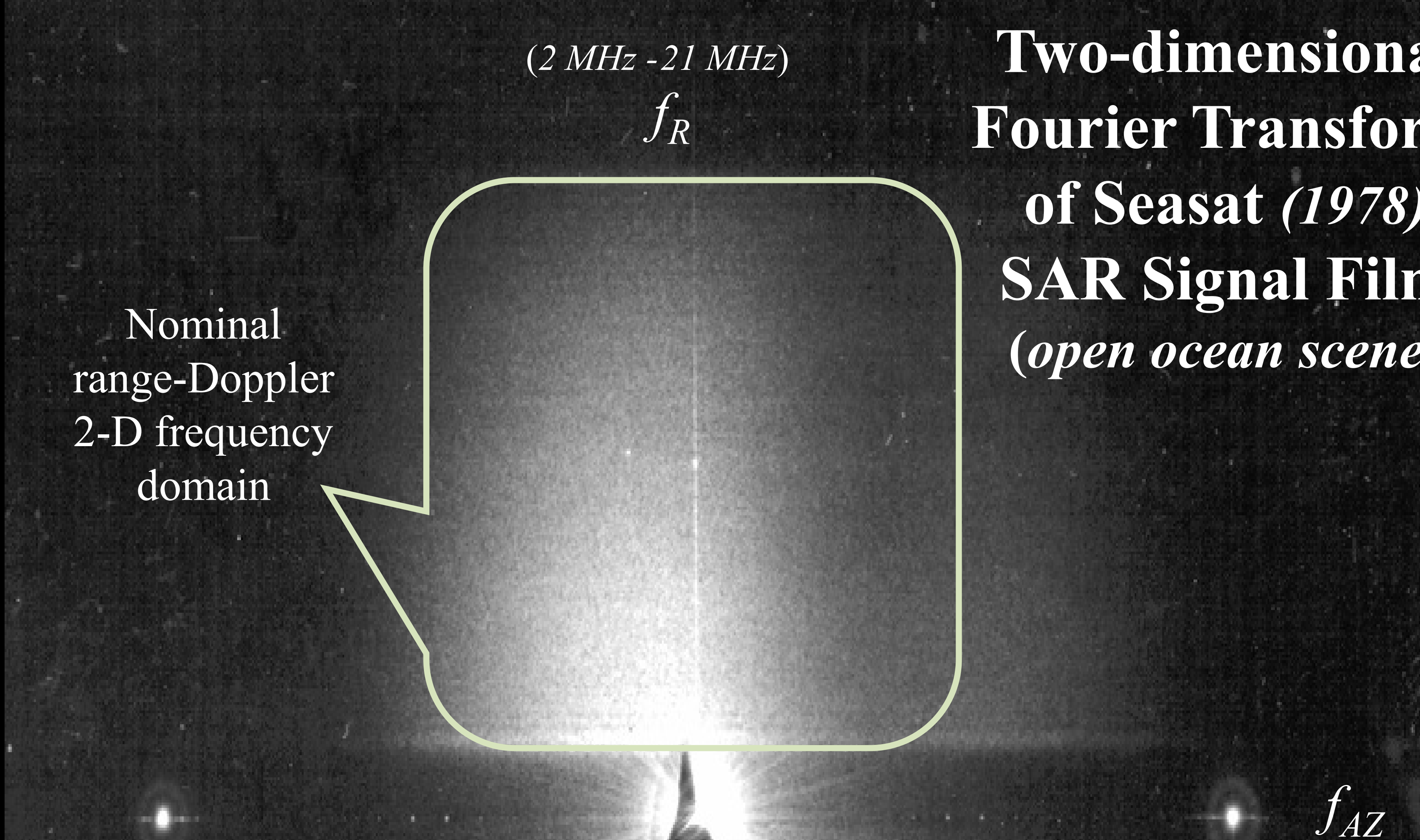
Two-dimensional Fourier Transform of Seasat *(1978)* SAR Signal Film (*open ocean scene*)



Two-dimensional Fourier Transform of Seasat *(1978)* SAR Signal Film (*open ocean scene*)

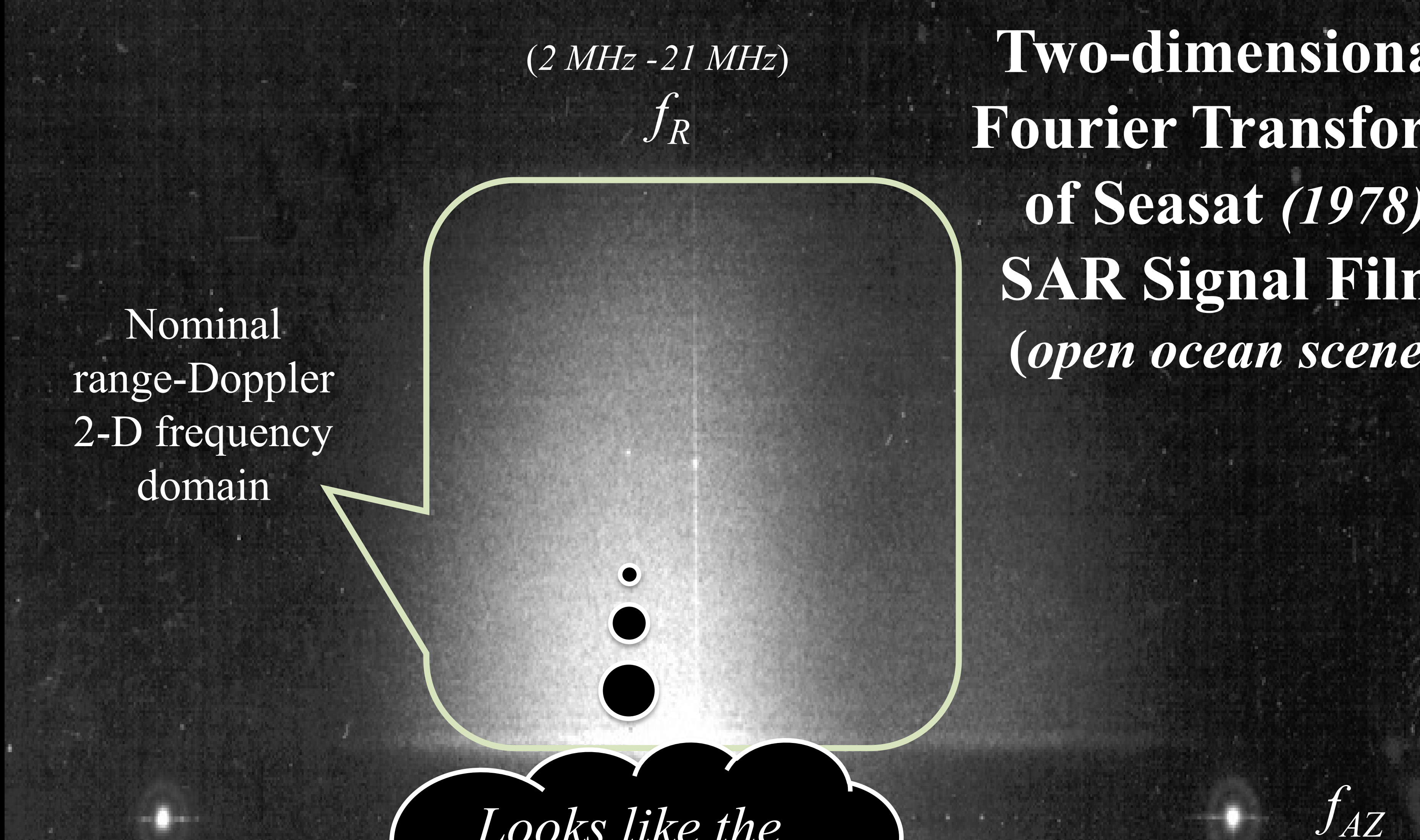


Two-dimensional Fourier Transform of Seasat *(1978)* SAR Signal Film (*open ocean scene*)

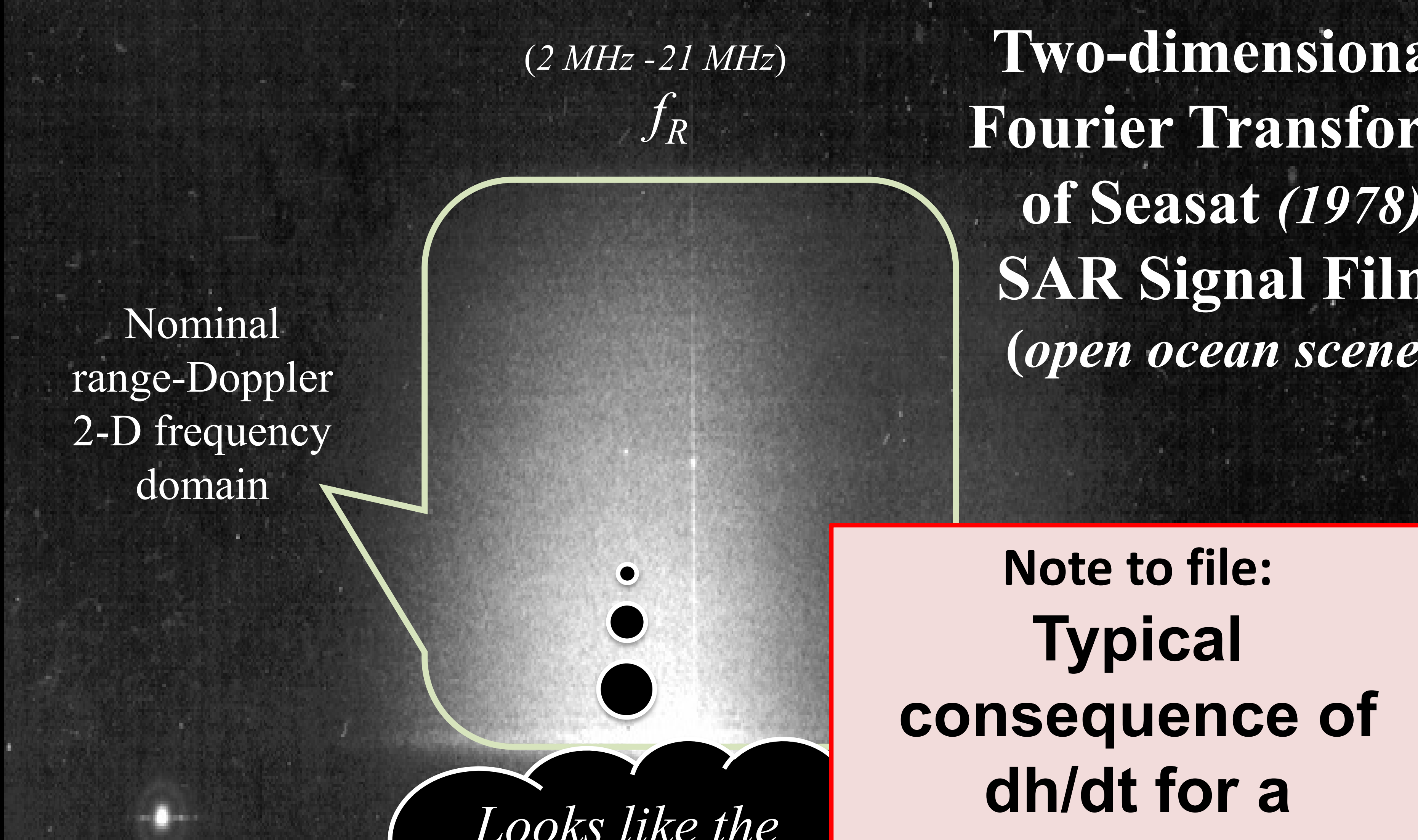


PRF ± 60 Hz

Two-dimensional Fourier Transform of Seasat *(1978)* SAR Signal Film (*open ocean scene*)



Two-dimensional Fourier Transform of Seasat *(1978)* SAR Signal Film (*open ocean scene*)



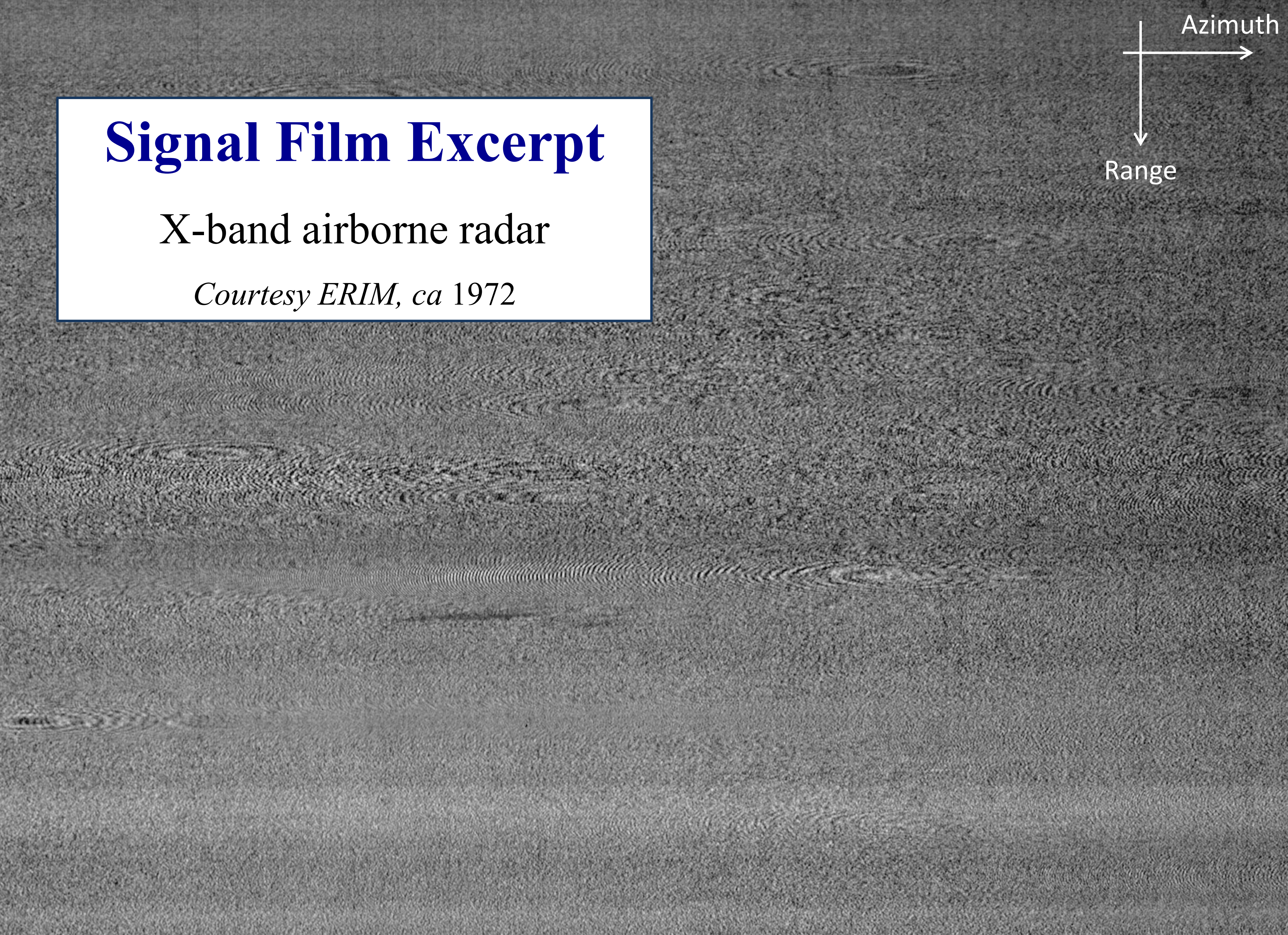
Looks like the spectrum is Doppler shifted

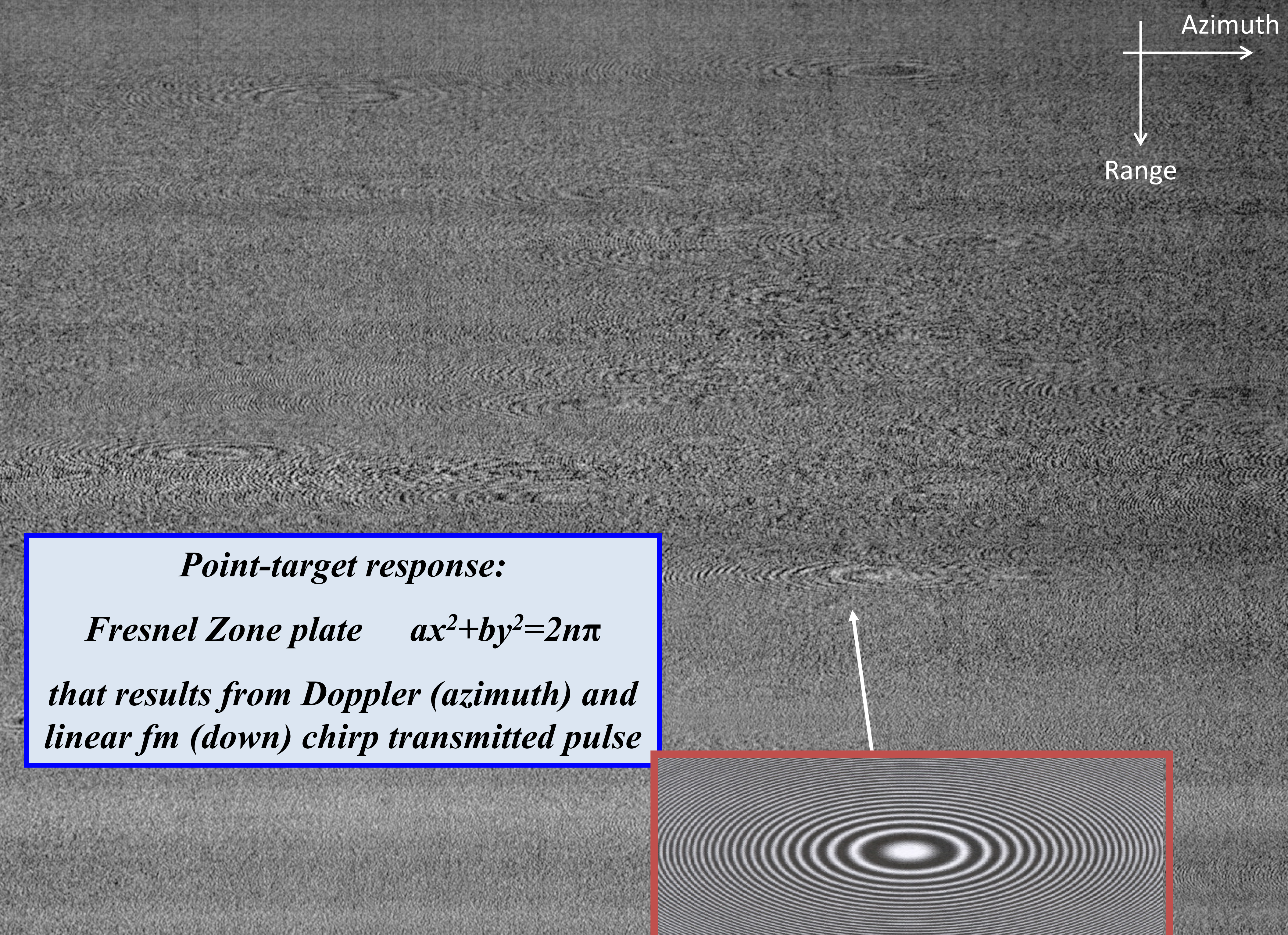
Note to file:
Typical consequence of dh/dt for a coherent orbital

Signal Film Excerpt

X-band airborne radar

Courtesy ERIM, ca 1972

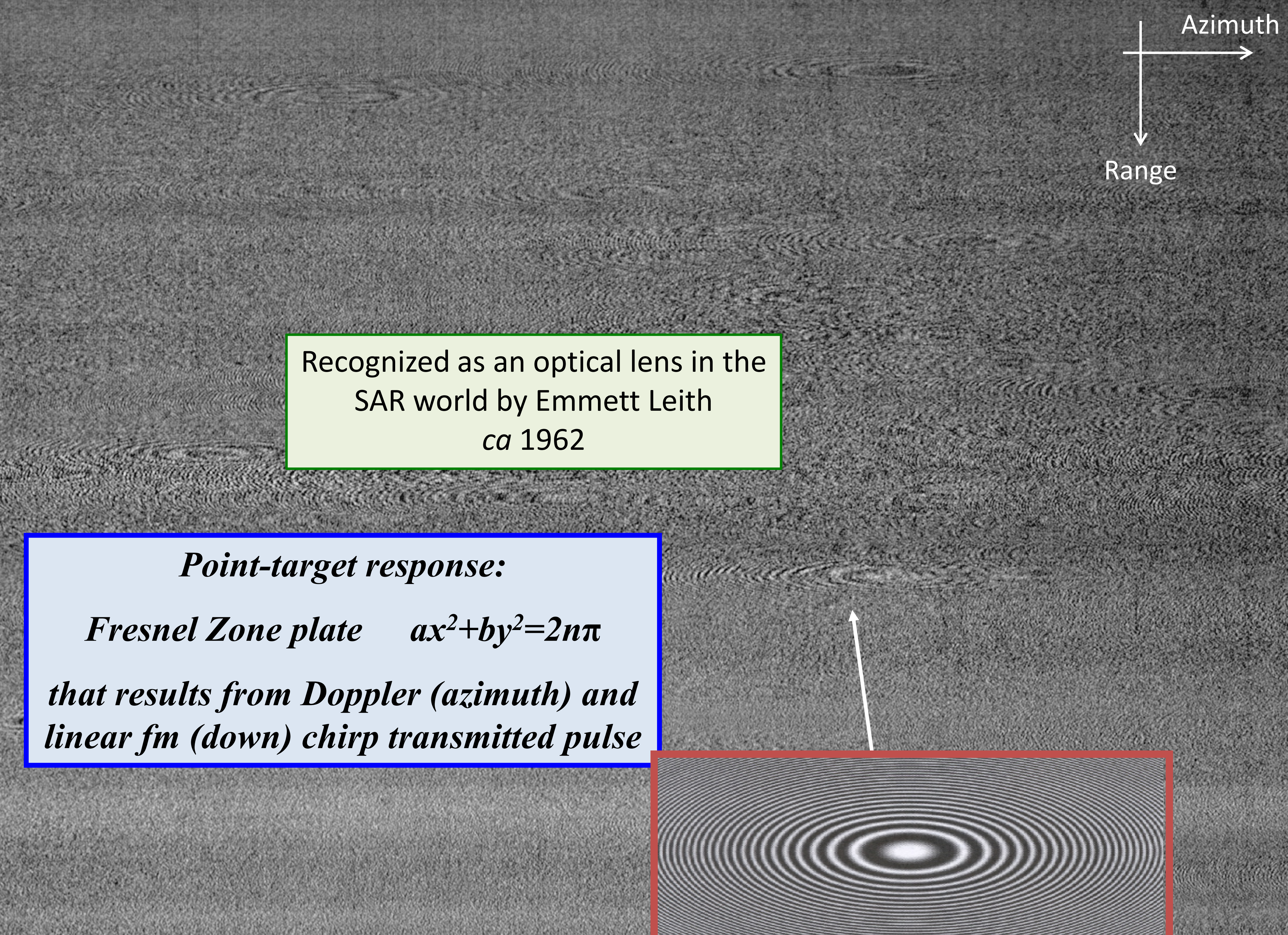




Point-target response:

Fresnel Zone plate $ax^2+by^2=2n\pi$

that results from Doppler (azimuth) and linear fm (down) chirp transmitted pulse



Recognized as an optical lens in the SAR world by Emmett Leith *ca* 1962

Point-target response:

Fresnel Zone plate $ax^2+by^2=2n\pi$

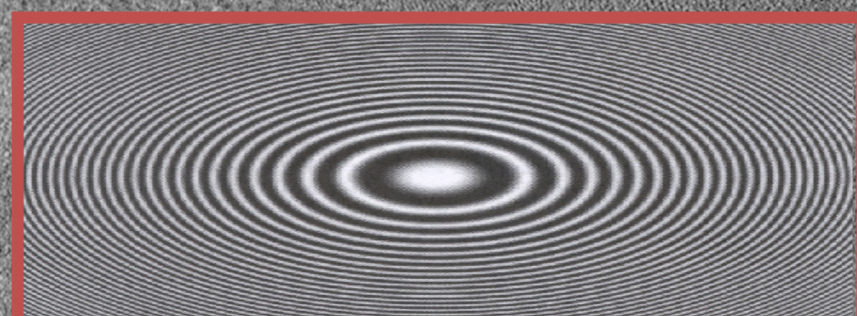
that results from Doppler (azimuth) and linear fm (down) chirp transmitted pulse

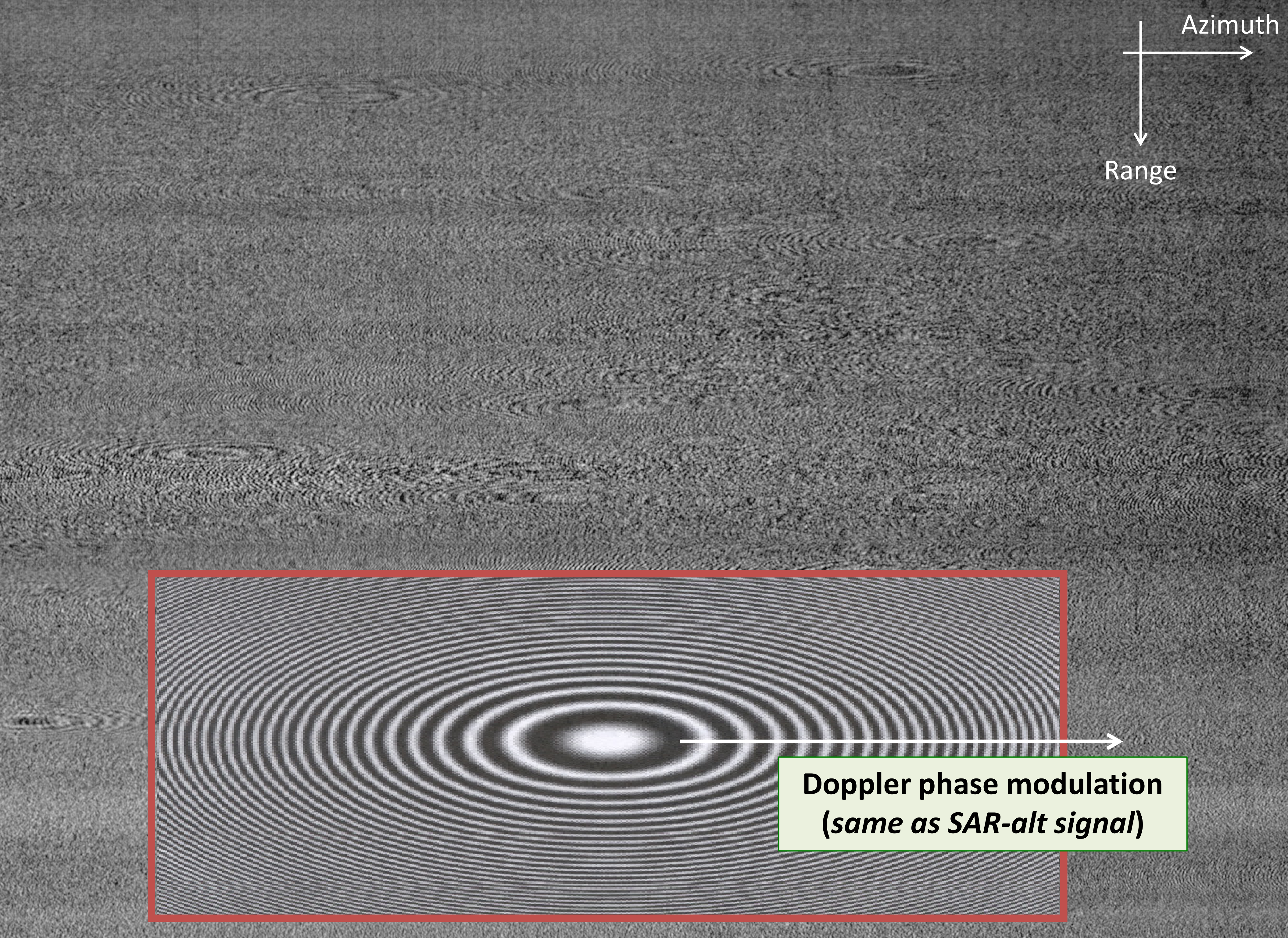
Azimuth

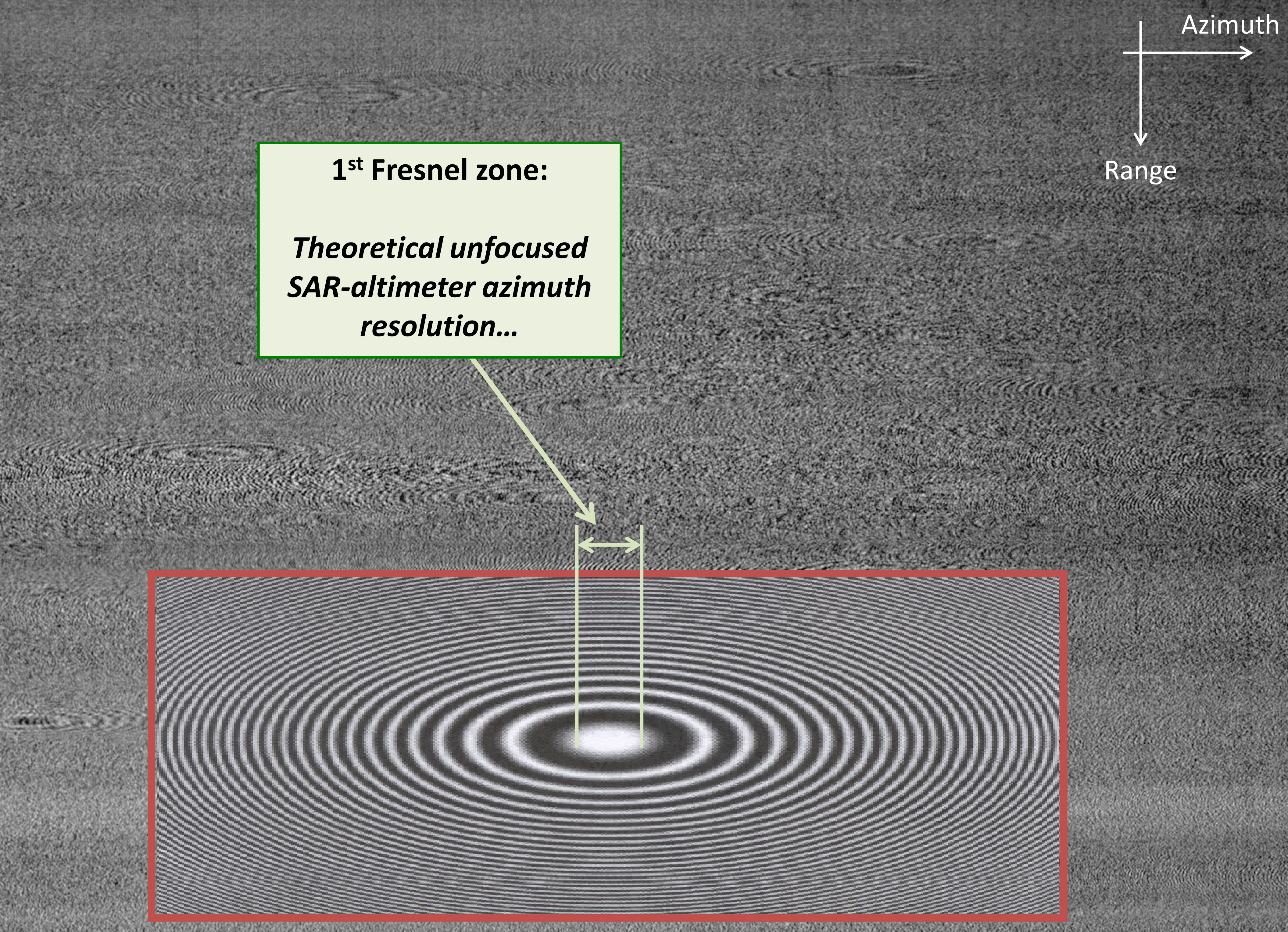
Range

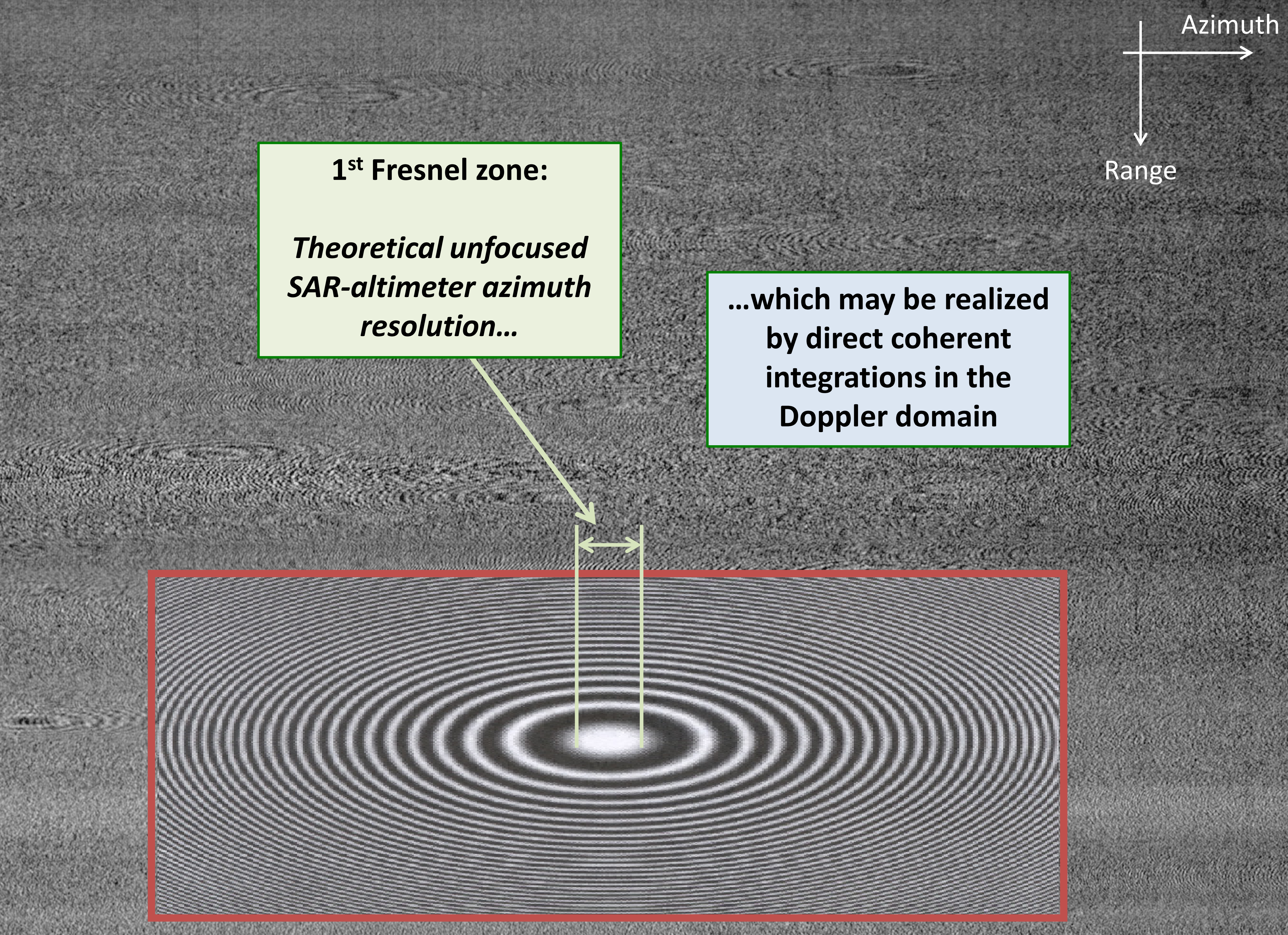
A timely tribute . .

Augustin-Jean Fresnel (1816) "Mémoire sur la Diffraction de la lumière, où l'on examine particulièrement le phénomène des franges colorées que présentent les ombres des corps éclairés par un point lumineux", *Annales de la Chimie et de Physique*, 2nd series, vol. 1, pages 239–281. (Presented before *l'Académie des sciences* on 15 October 1815.)

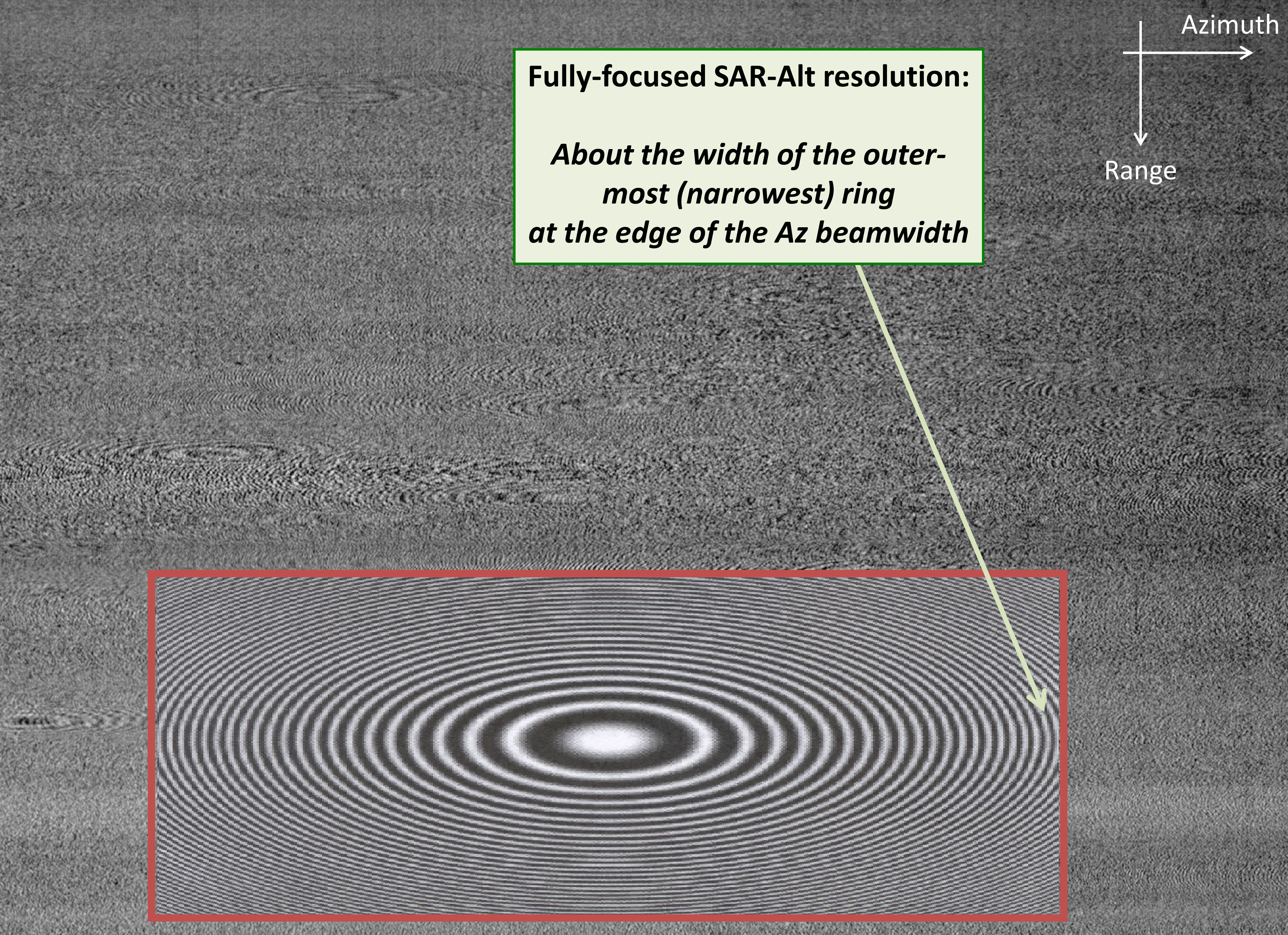



Azimuth
Range
Doppler phase modulation
(*same as SAR-alt signal*)


Azimuth
Range
1st Fresnel zone:
Theoretical unfocused SAR-altimeter azimuth resolution…



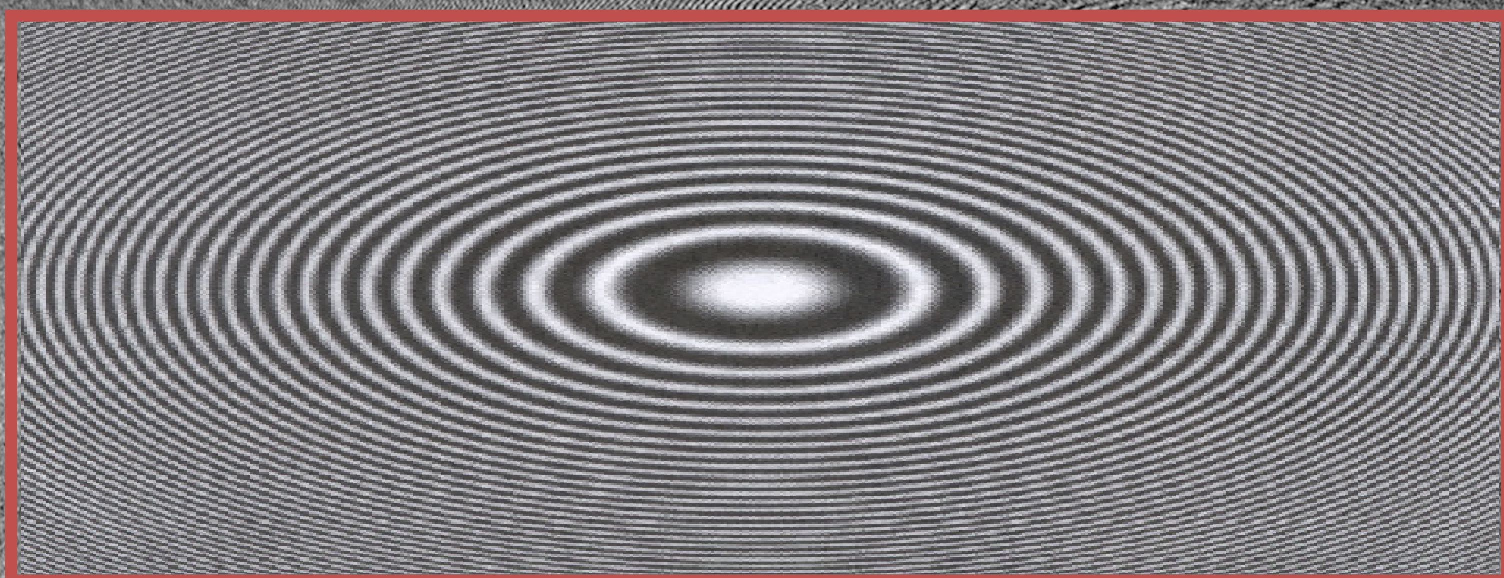
Azimuth
Range
1st Fresnel zone:
Theoretical unfocused SAR-altimeter azimuth resolution…
…which may be realized by direct coherent integrations in the Doppler domain



Fully-focused SAR-Alt resolution:
About the width of the outer-most (narrowest) ring at the edge of the Az beamwidth
Azimuth
Range

Phase preservation in the signal domain is essential

(coherence)



Lessons Learned: Precedent

- *Related fields (e.g. sounding, optics) can be instructive*

Lessons Learned: Precedent

- ***Related fields (e.g. sounding, optics) can be instructive***
- ***Many prior SAR-enhanced altimeter references***

Lessons Learned: Precedent

- *Related fields (e.g. sounding, optics) can be instructive*
- *Many prior SAR-enhanced altimeter references*
- *Improvements using SAR "tricks" a worthy goal . . .*

  . . . but there is more to it than finer resolution.

Lessons Learned: Precedent

- *Related fields (e.g. sounding, optics) can be instructive*
- *Many prior SAR-enhanced altimeter references*
- *Improvements using SAR "tricks" a worthy goal . . .*

  . . . but there is more to it than finer resolution.
- *Small measurement SD desirable (requires looks)*

Lessons Learned: Precedent

- *Related fields (e.g. sounding, optics) can be instructive*
- *Many prior SAR-enhanced altimeter references*
- *Improvements using SAR "tricks" a worthy goal . . .*
  . . . but there is more to it than finer resolution.
- *Small measurement SD desirable (requires looks)*
- *Raw signal must preserve phase (coherence)*

Lessons Learned: Precedent

- *Related fields (e.g. sounding, optics) can be instructive*
- *Many prior SAR-enhanced altimeter references*
- *Improvements using SAR "tricks" a worthy goal . . .*
  . . . but there is more to it than finer resolution.
- *Small measurement SD desirable (requires looks)*
- *Raw signal must preserve phase (coherence)*
- *Spurious Dopplers (e.g. dh/dt) must be eliminated*

Lessons Learned: Precedent

- *Related fields (e.g. sounding, optics) can be instructive*
- *Many prior SAR-enhanced altimeter references*
- *Improvements using SAR "tricks" a worthy goal . . .*

  . . . but there is more to it than finer resolution.
- *Small measurement SD desirable (requires looks)*
- *Raw signal must preserve phase (coherence)*
- *Spurious Dopplers (e.g. dh/dt) must be eliminated*
- *SAR-alt processing simpler, AND more challenging*

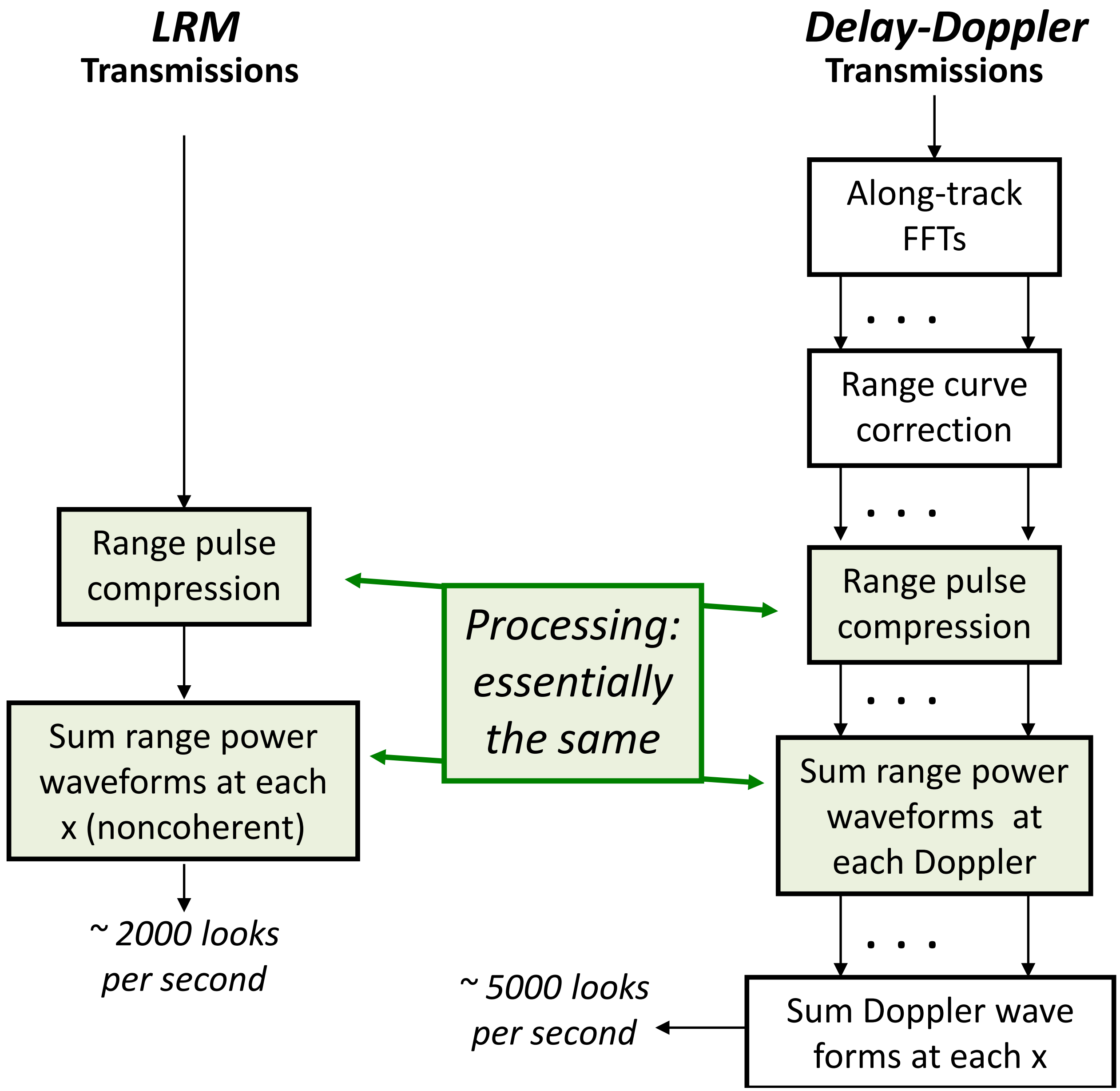
Lessons Learned: Precedent

- *Related fields (e.g. sounding, optics) can be instructive*
- *Many prior SAR-enhanced altimeter references*
- *Improvements using SAR "tricks" a worthy goal . . .*
  . . . but there is more to it than finer resolution.
- *Small measurement SD desirable (requires looks)*
- *Raw signal must preserve phase (coherence)*
- *Spurious Dopplers (e.g. dh/dt) must be eliminated*
- *SAR-alt processing simpler, AND more challenging*
- *Burst (unfocused) mode: a reasonable starting point*

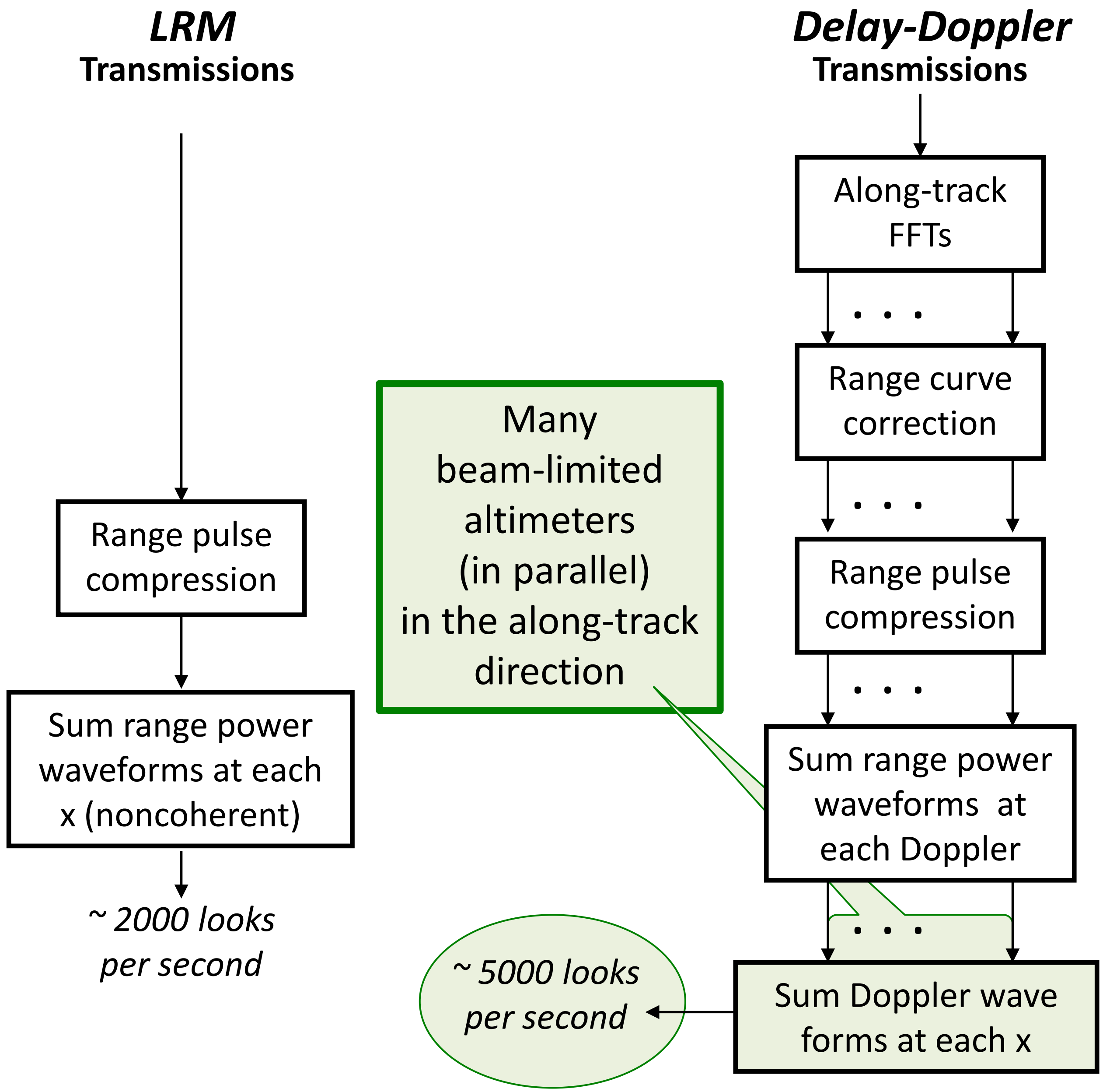
CryoSat-2 (*April 2010 Launch*)

(a new paradigm in Earth observation altimeters)

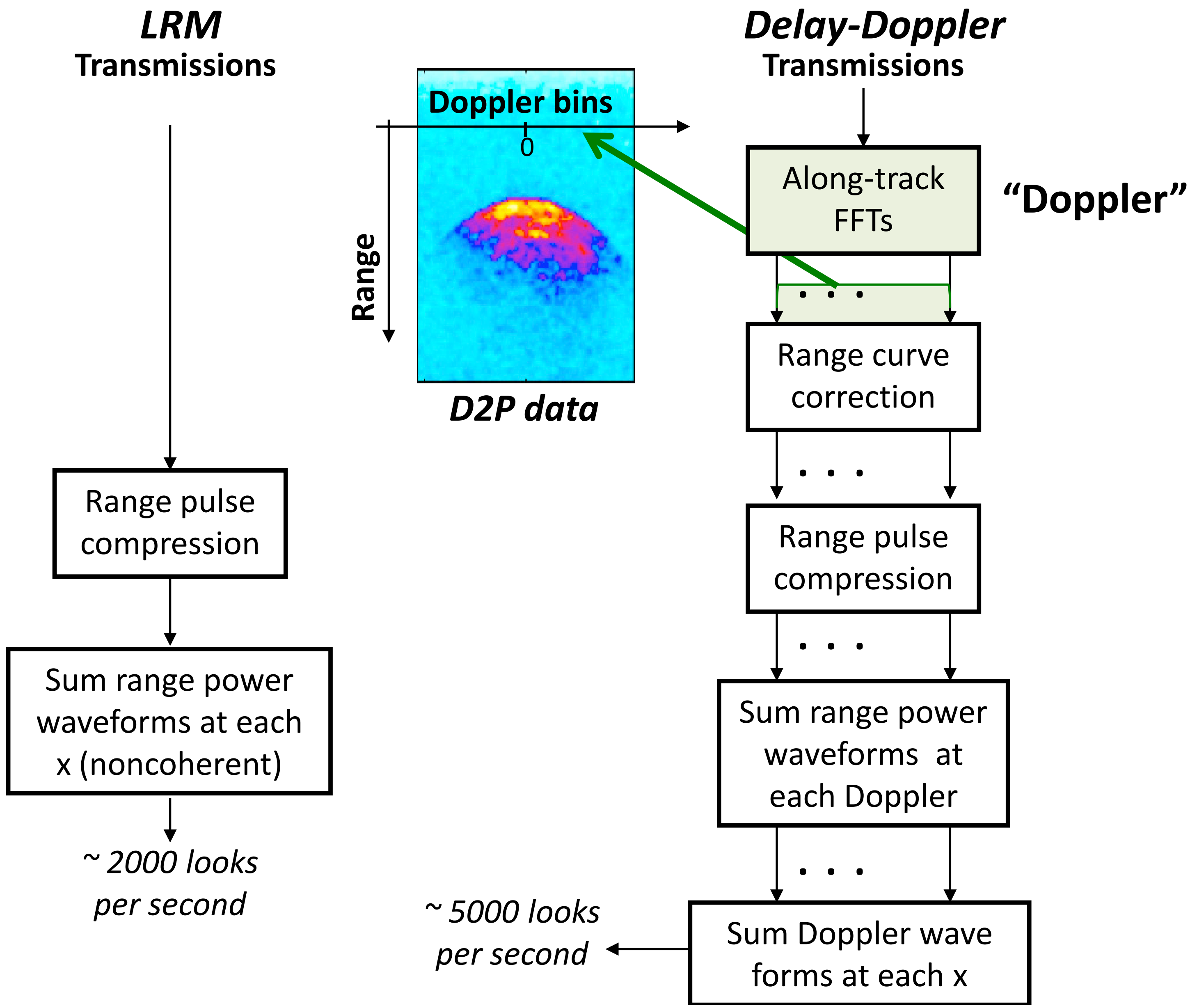
Unfocused SAR mode Altimetry



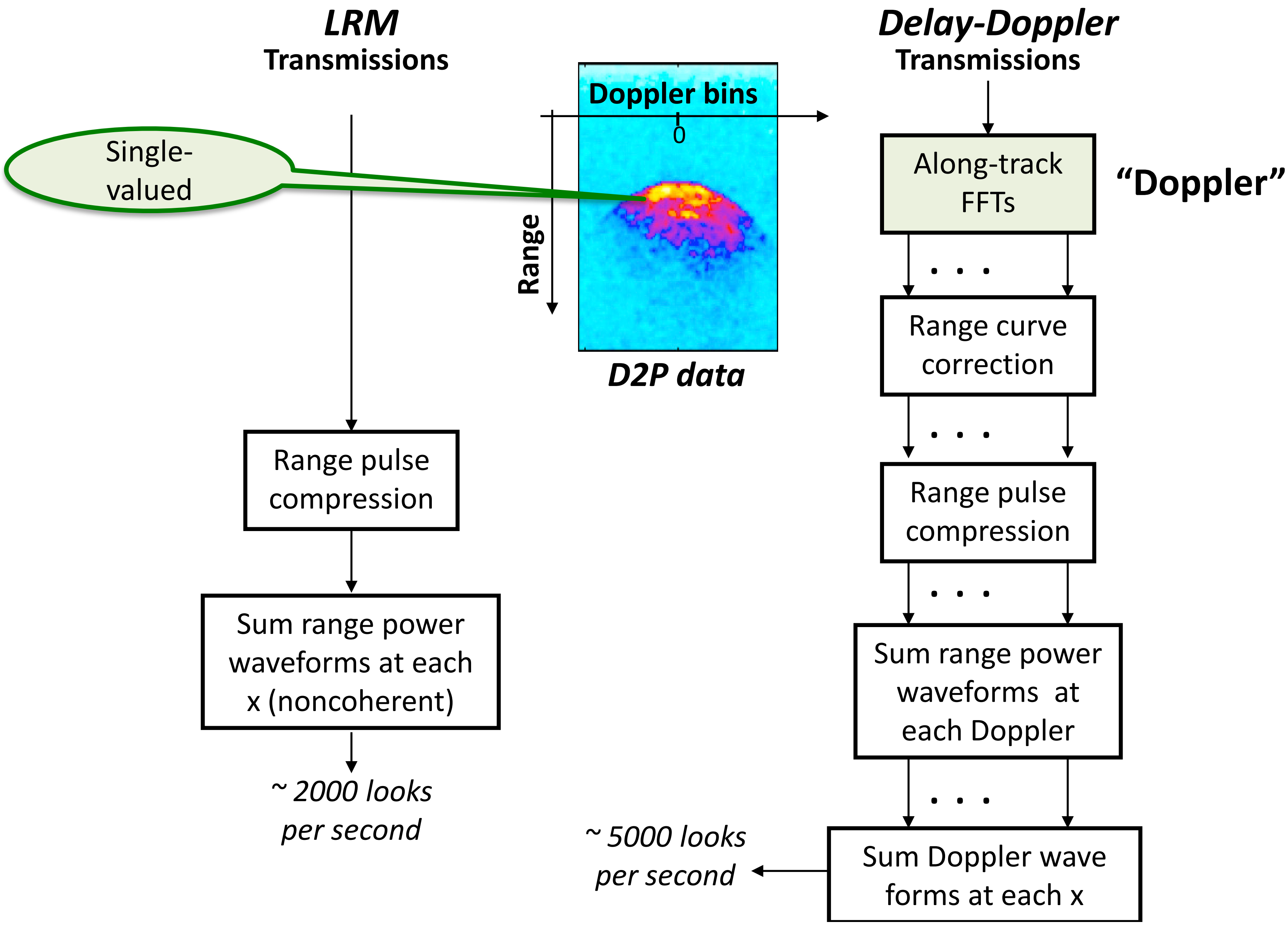
Unfocused SAR mode Altimetry



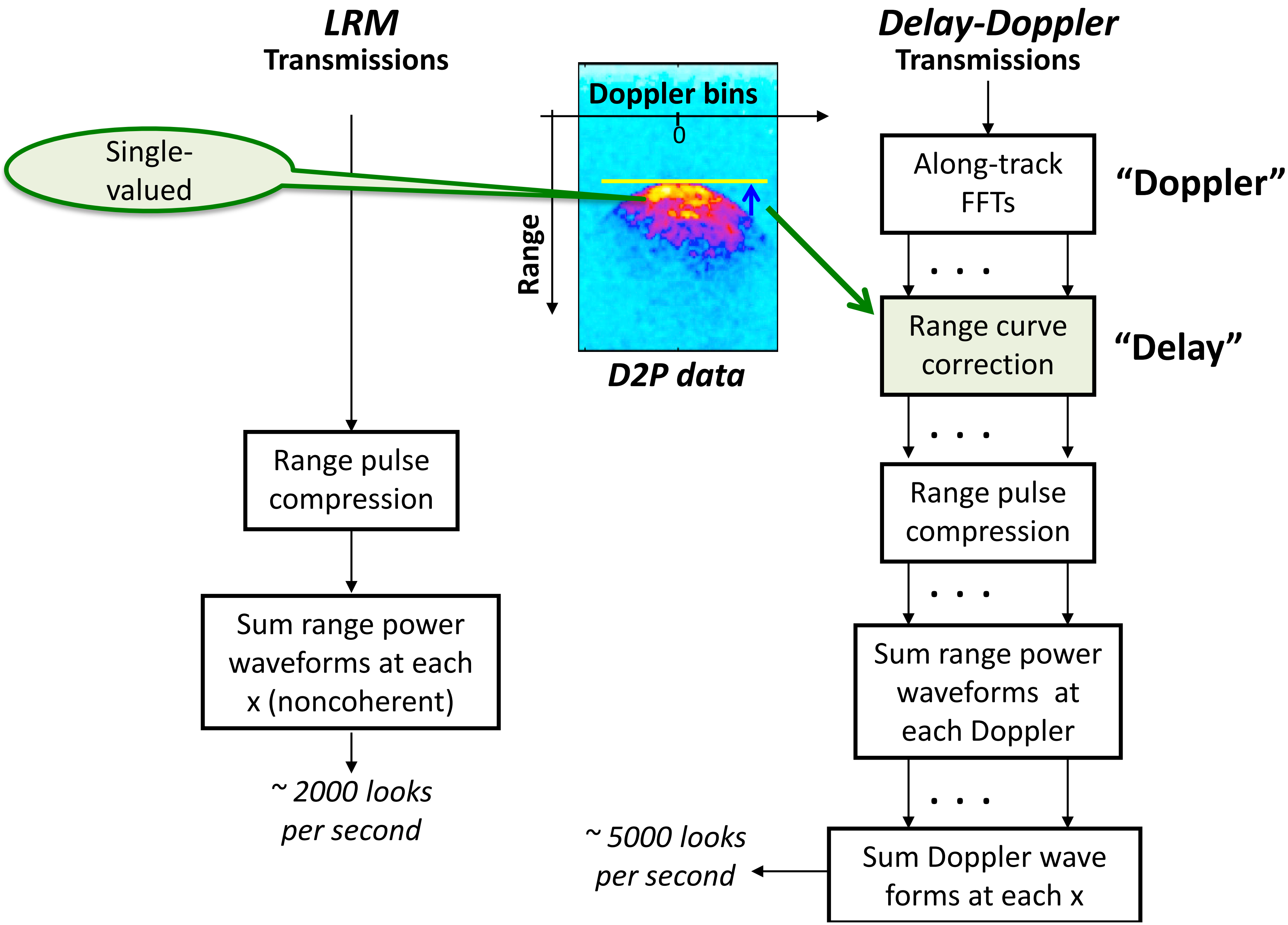
Unfocused SAR mode Altimetry



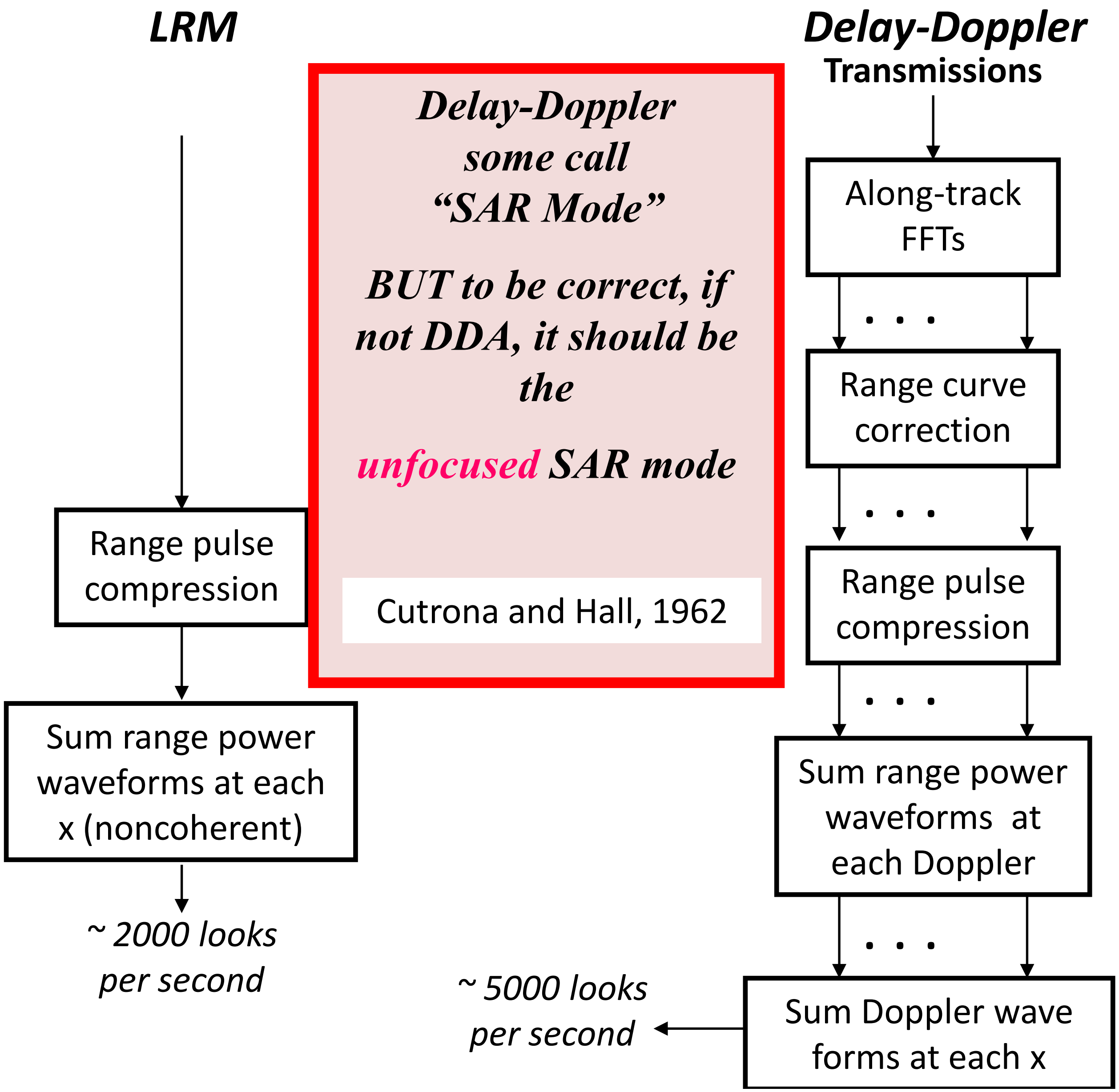
Unfocused SAR mode Altimetry



Unfocused SAR mode Altimetry



Unfocused SAR mode Altimetry



Unfocused SAR mode Altimetry

LRM

Range pulse compression

Sum range power waveforms at each x (noncoherent)

~ 2000 looks per second

Delay-Doppler some call "SAR Mode"

BUT to be correct, if not DDA, it should be the

unfocused SAR mode

because "SAR Mode" implies azimuth "focusing" filters

Delay-Doppler
Transmissions

Along-track FFTs

. . .

Range curve

Azimuth focus operator

. . .

Range pulse compression

. . .

Sum range power waveforms at each Doppler

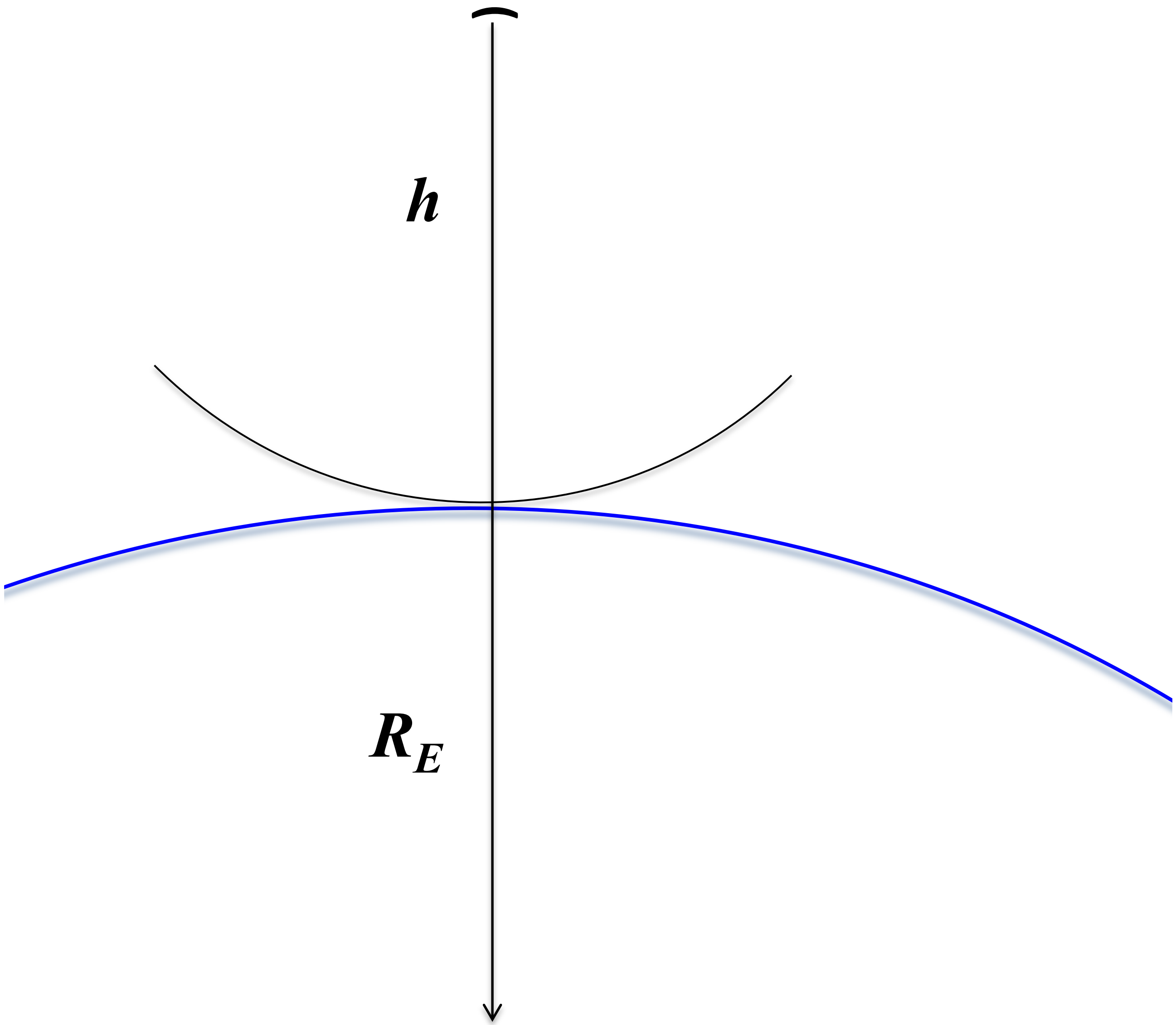
. . .

Sum Doppler wave forms at each x

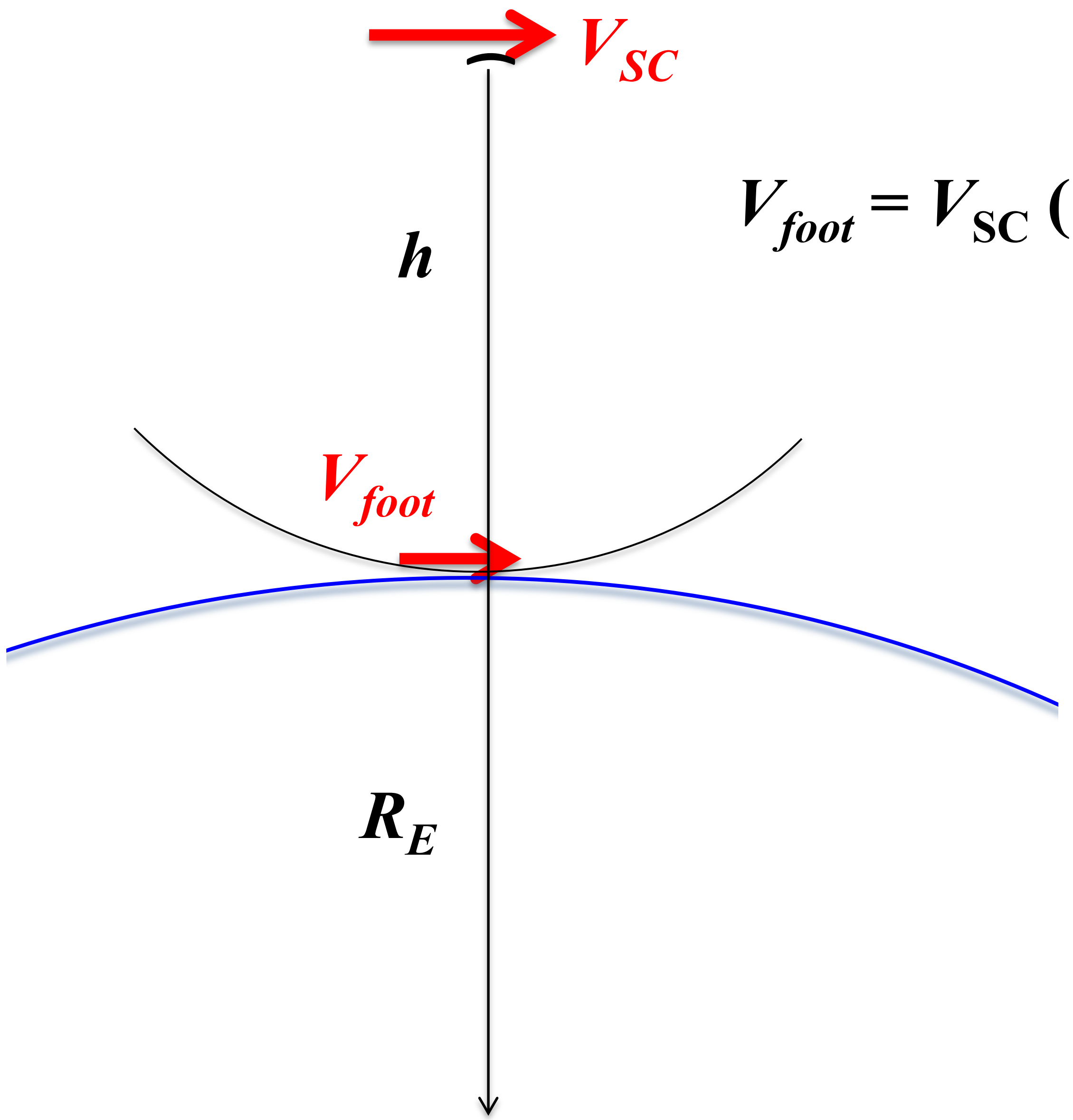
~ 5000 looks per second

Altimeter in Orbit

The spherical geometry is helpful

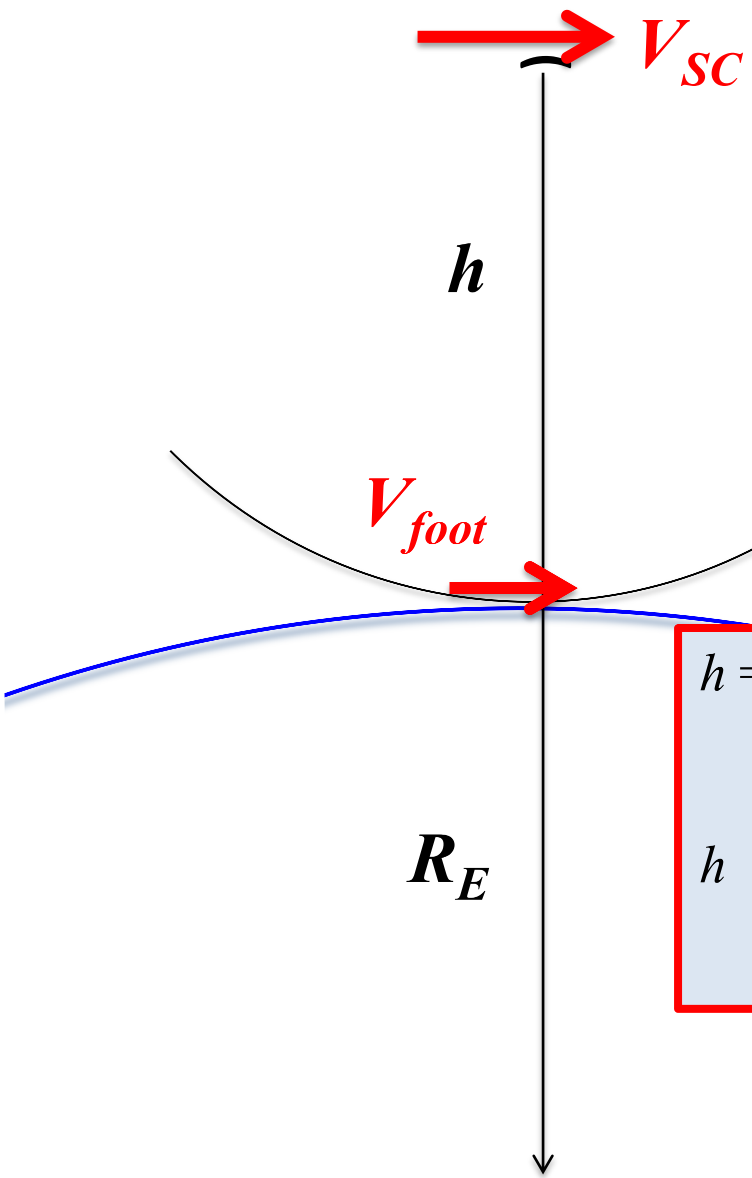


Velocities



$$V_{foot} = V_{\mathrm{SC}}\,(1 + h/R_E\,)^{-1}$$

Velocities

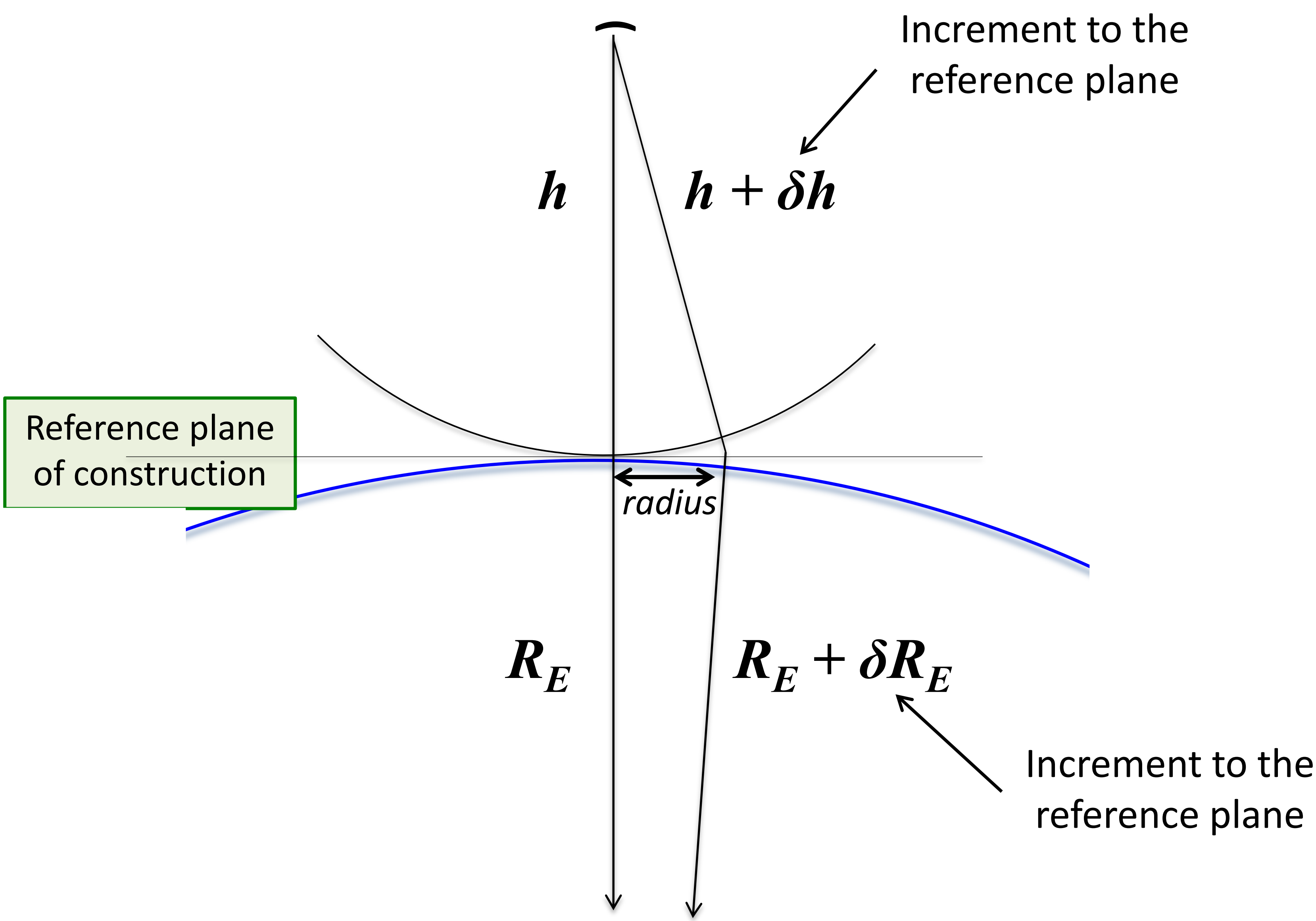


$$V_{foot} = V_{\mathrm{SC}} \, (1 + h/R_E)^{-1}$$

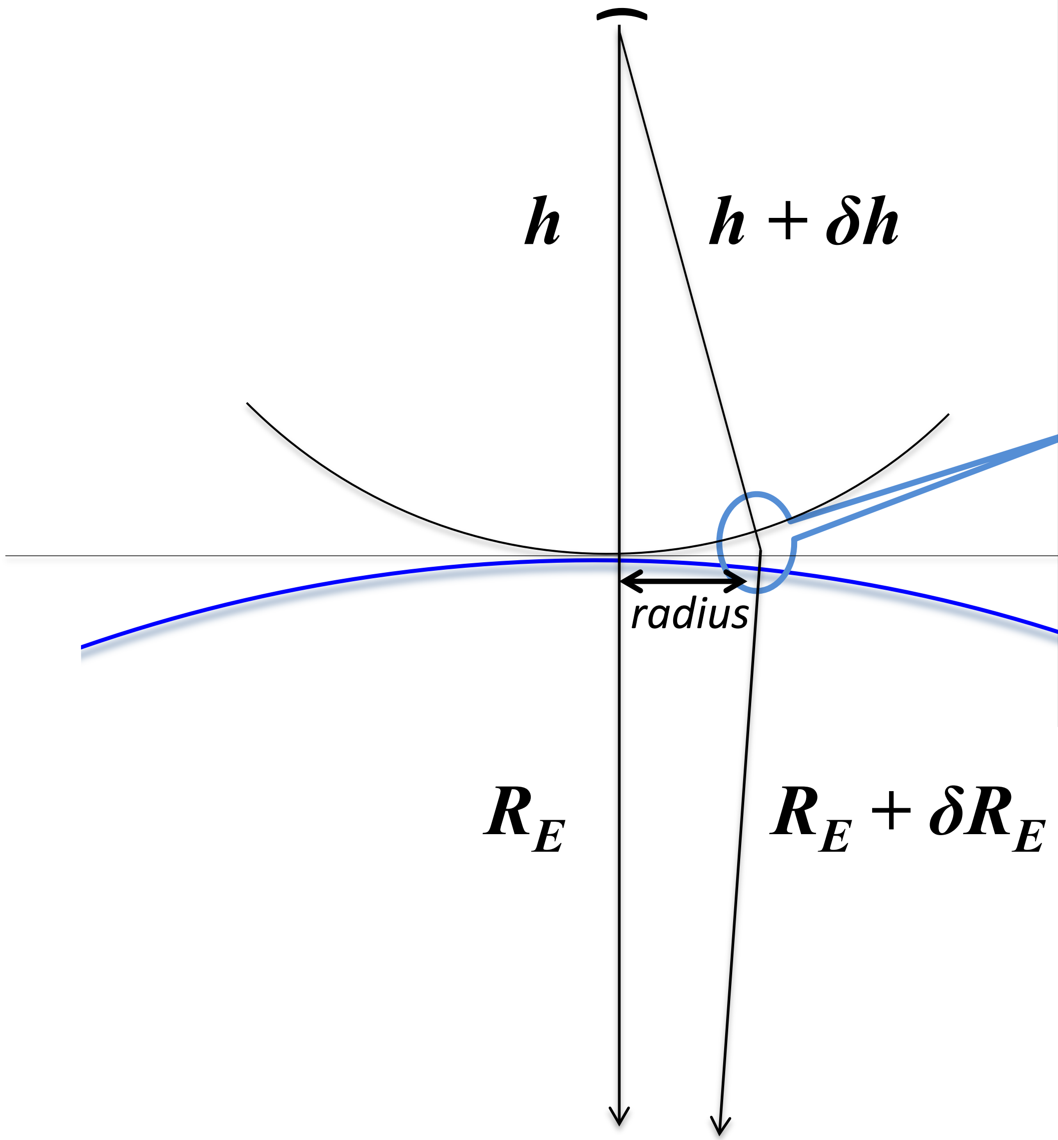
$h = 717$ km
$V_{SC} = 7490$ m/s $\quad V_{foot} = 6732$ m/s

$h = 1335$ km
$V_{SC} = 7184$ m/s $\quad V_{foot} = 5939$ m/s

Along-Track Dimensions



Along-Track Dimensions



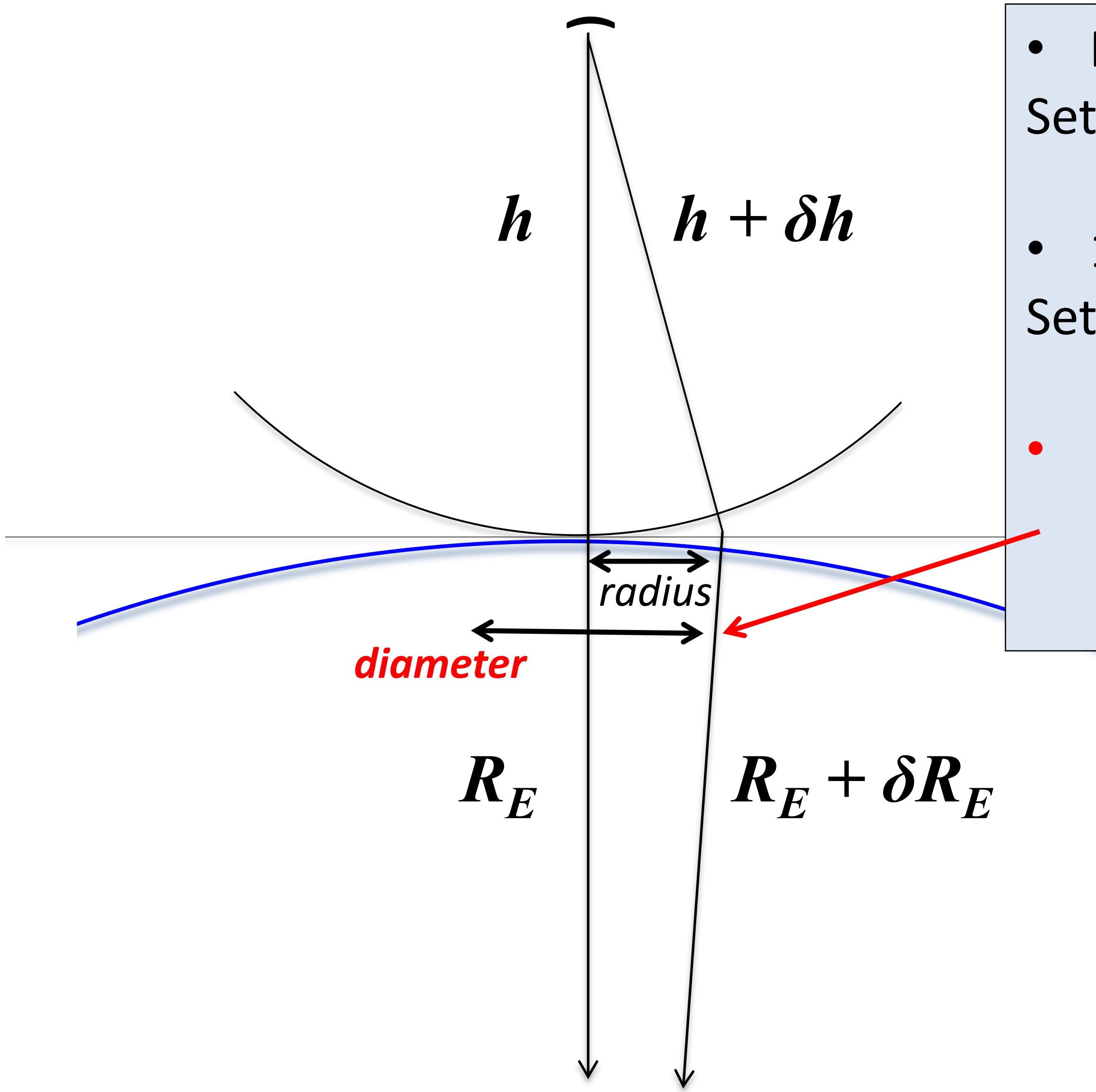
- Pulse-limited radius:

Set $\delta h + \delta R_E = \rho_{rng}/2$

- 1st Fresnel zone radius:

Set $\delta h + \delta R_E = \lambda/4$

Along-Track Dimensions



- Pulse-limited radius:

Set $\delta h + \delta R_E = \rho_{rng}/2$

- 1st Fresnel zone radius:

Set $\delta h + \delta R_E = \lambda/4$

- ***Alert:***

length (or diameter)

$X = 2 \times radius$

Typical Along Track Sizes

Altitude (km)	717	1335	Altitude x beamwidth
Antenna *foot*print length (km)	16	30	$X_{foot} = h(\lambda / D)$

Typical Along Track Sizes

Altitude (km)	717	1335
Antenna *foot*print length (km)	16	30
*P*ulse-*L*imited diameter (m)	1135	1486

Typical Along Track Sizes

Altitude (km)	717	1335
*P*ulse-*L*imited diameter (m)	1135	1486
*unf*ocused resolution (m)	168	220

$$X_{PL} \approx 2\sqrt{\rho_{rng} h \left(1 + h / R_E\right)^{-1}}$$

$$\rho_{unf} = \sqrt{2h\lambda\left(1 + h / R_E\right)^{-1}}$$

Typical Along Track Sizes

Altitude (km)	717	1335	
*P*ulse-*L*imited diameter (m)	1135	1486	$X_{PL} \approx 2\sqrt{\rho_{rng} h \left(1 + h / R_E\right)^{-1}}$
*unf*ocused resolution (m)	168	220	$\rho_{unf} = \sqrt{2h\lambda\left(1 + h / R_E\right)^{-1}}$

About 7 times smaller than X_{PL}

Typical Along Track Sizes

Altitude (km)	717	1335	
Doppler bin (m)	300	560	$X_{Dop} = \frac{f_{prf} h \lambda}{2 V_{SC} N_B}$
unfocused resolution (m)	168	220	$\rho_{unf} = \sqrt{2 h \lambda \left(1 + h / R_E\right)^{-1}}$

Typical Along Track Sizes

Altitude (km)	717	1335	
*Dop*pler bin (m)	300	560	$X_{Dop} = \dfrac{f_{prf} h\lambda}{2V_{SC}N_B}$
*unf*ocused resolution (m)	168	220	$\rho_{unf} = \sqrt{2h\lambda\left(1+h/R_E\right)^{-1}}$

1st Fresnel zone diameter

Physics

Typical Along Track Sizes

Altitude (km)		717	1335	
Doppler bin (m)	***CryoSat***	300	560	$X_{Dop} = \dfrac{f_{prf} h \lambda}{2 V_{SC} N_B}$
unfocused resolution (m)		168	220	$\rho_{unf} = \sqrt{2h\lambda\left(1 + h/R_E\right)^{-1}}$

Radar

Physics

Typical Along Track Sizes

Closed burst length L_B

$$\frac{1}{L_B} = \frac{f_{prf}}{N_B} > \frac{c}{2h}$$

is bounded above . . .

Altitude (km)		717		
Doppler bin (m)	***CryoSat***	300	560	$X_{Dop} = \frac{f_{prf} h\lambda}{2V_{SC} N_B}$
unfocused resolution (m)		168	220	$\rho_{unf} = \sqrt{2h\lambda\left(1 + h/R_E\right)^{-1}}$

Typical Along Track Sizes

Altitude (km)		717	1335	

. . . hence

$$Minimum\left[X_{Dop}\right]_{closed} = b\frac{c\lambda}{4V_{SC}} > \rho_{unf}$$

where $b \sim 1.5$

*Do*ppler bin (m)	*CryoSat*	300	560	$X_{Dop} = \frac{f_{prf}h\lambda}{2V_{SC}N_B}$
*unf*ocused resolution (m)		168	220	$\rho_{unf} = \sqrt{2h\lambda\left(1+h/R_E\right)^{-1}}$

Typical Along Track Sizes

Altitude (km)	717	1335
Antenna *foot*print length (km)	16	30
*P*ulse-*L*imited diameter (m)	1135	1486
*Dop*pler bin (m)	300	560
*unf*ocused resolution (m)	168	220
One-look *SAR* resolution (m)	0.45	0.41

$$\rho_1 = \frac{D}{2}\left(1 + h / R_E\right)^{-1}$$

Antenna diameter D = 1 m

Lessons Learned: Present

- *CryoSat has met expectations, and much more*

Lessons Learned: Present

- *CryoSat has met expectations, and much more*
- *Closed burst => two limiting characteristics*

  Listening time smaller × *3* *and* $X_{Dop} > \rho_{unf}$

Lessons Learned: Present

- *CryoSat has met expectations, and much more*
- *Closed burst => <u>two</u> limiting characteristics*

  Listening time smaller × 3 *and* $X_{Dop} > \rho_{unf}$

- *Maximizing performance <u>requires</u> open/interleaved*

Lessons Learned: Present

- *CryoSat has met expectations, and much more*
- *Closed burst => two limiting characteristics*

  Listening time smaller × *3* *and* $X_{Dop} > \rho_{unf}$
- *Maximizing performance requires open/interleaved*
- *Single-look fully-focused resolution < $D/2$*

Lessons Learned: Present

- *CryoSat has met expectations, and much more*
- *Closed burst => two limiting characteristics*

  Listening time smaller $\times$ *3* *and* $X_{Dop} > \rho_{unf}$
- *Maximizing performance requires open/interleaved*
- *Single-look fully-focused resolution < D/2*
- *But what about statistically-independent looks ?*

N: Number of Looks per Second

Altitude (km)	717	1335
	Looks per second	
Present $N_{\text{LRM/Walsh}}$	2100	1400
$N_{\text{unfocused, closed, } X\text{dop}}$	2700	1400
Prospects $N_{\text{unfocused, (closed), Fresnel}}$	4700	3500
$N_{\text{unfocused, open, } X\text{dop}}$	8100	4100
$N_{\text{unfocused, open, Fresnel}}$	14000	10600
$N_{\text{SAR, fully focused}}$	14800	14400

N: Number of Looks per Second

Altitude (km)		717	1335	
		Looks per second		
Present	$N_{\text{LRM/Walsh}}$	2100	1400	→ W
	$N_{\text{unfocused, closed, } X\text{dop}}$	2700	1400	
Prospects	$N_{\text{unfocused, (closed), Fresnel}}$	4700	3500	
	$N_{\text{unfocused, open, } X\text{dop}}$	8100	4100	
	$N_{\text{unfocused, open, Fresnel}}$	14000	10600	
	$N_{\text{SAR, fully focused}}$	$7 \times W \approx 14800$	$14400 \approx 10 \times W$	

Open vs Closed Burst

Altitude (km)	717	1335
	Looks per second	
$N_{\text{LRM/Walsh}}$	2100	1400
$N_{\text{unfocused, closed, }X\text{dop}}$	2700	1400
$N_{\text{unfocused, (closed), Fresnel}}$	4700	3500
$N_{\text{unfocused, open, }X\text{dop}}$	8100	4100
$N_{\text{unfocused, open, Fresnel}}$	14000	10600
$N_{\text{SAR, fully focused}}$	14800	14400

Present

Prospects

Open vs closed burst: *~ 3 times more looks*

Unfocused processing can be very good

	Altitude (km)	717	1335
		Looks per second	
Present	$N_{\text{LRM/Walsh}}$	2100	1400
Present	$N_{\text{unfocused, closed, }X\text{dop}}$	2700	1400
Prospects	$N_{\text{unfocused, (closed), Fresnel}}$	4700	3500
Prospects	$N_{\text{unfocused, open, }X\text{dop}}$	8100	4100
Prospects	$N_{\text{unfocused, open, Fresnel}}$	14000	10600
	$N_{\text{SAR, fully focused}}$	14800	14400

Unfocused processing can be very good

Altitude (km)	717	1335
	Looks per second	
$N_{\text{LRM/Walsh}}$	2100	1400
$N_{\text{unfocused, closed, }X\text{dop}}$	2700	1400
$N_{\text{unfocused, (closed), Fresnel}}$	4700	3500
$N_{\text{unfocused, open, }X\text{dop}}$	8100	4100
$N_{\text{unfocused, open, Fresnel}}$	14000	10600
$N_{\text{SAR, fully focused}}$	14800	14400

Present

Prospects

Unfocused burst mode in both cases, yet ***5 to 6 times more looks***

Unfocused processing can be very good

Present / **Prospects**

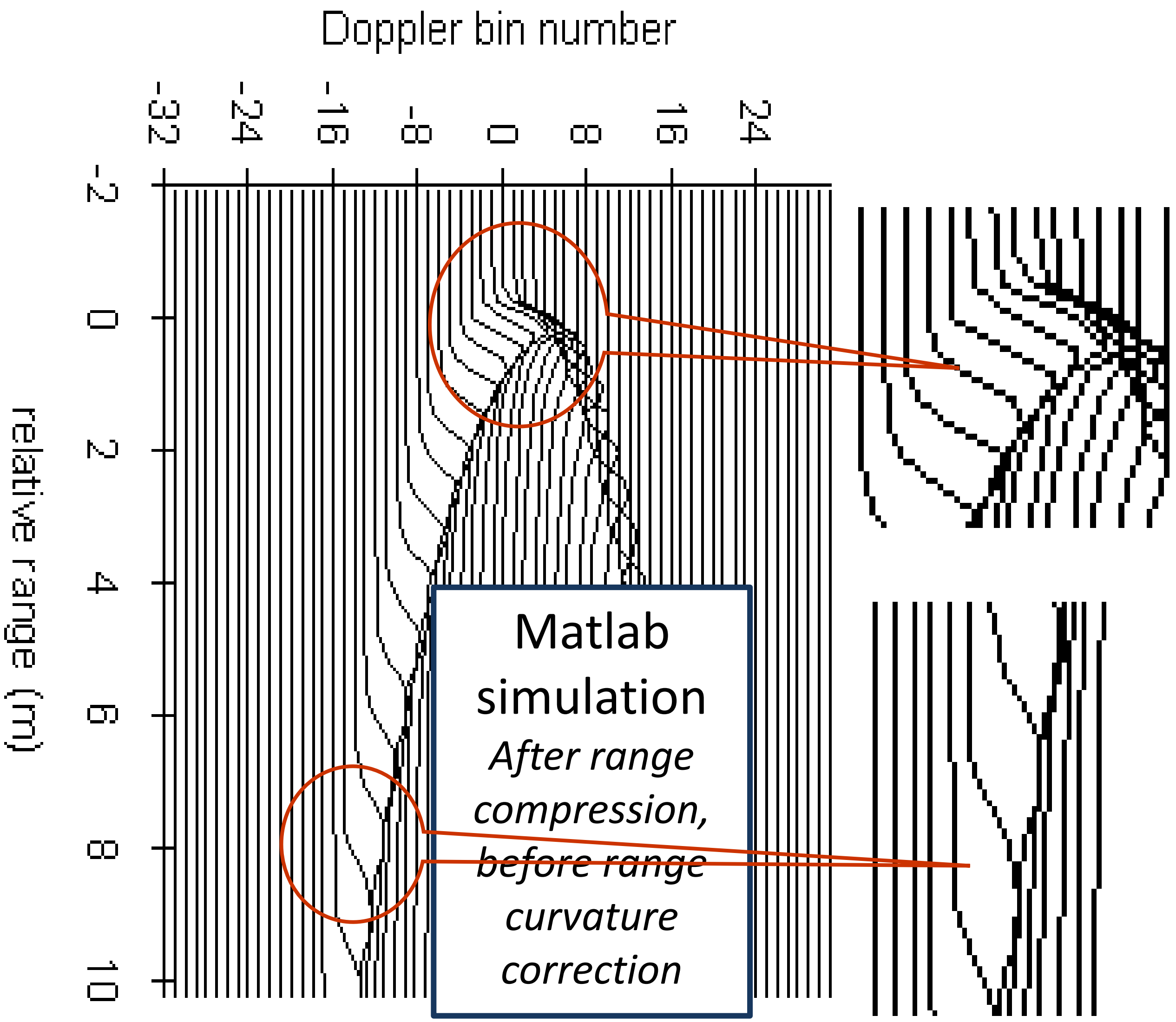
Altitude (km)	717	1335
	Looks per second	
$N_{\text{LRM/Walsh}}$	2100	1400
$N_{\text{unfocused, closed, } X\text{dop}}$	2700	1400
$N_{\text{unfocused, (closed), Fresnel}}$	4700	3500
$N_{\text{unfocused, open, } X\text{dop}}$	8100	4100
$N_{\text{unfocused, open, Fresnel}}$	14000	10600
$N_{\text{SAR, fully focused}}$	14800	14400

Why ?

Unfocused burst mode in both cases, yet ***5 to 6 times more looks***

Useful Doppler Bins

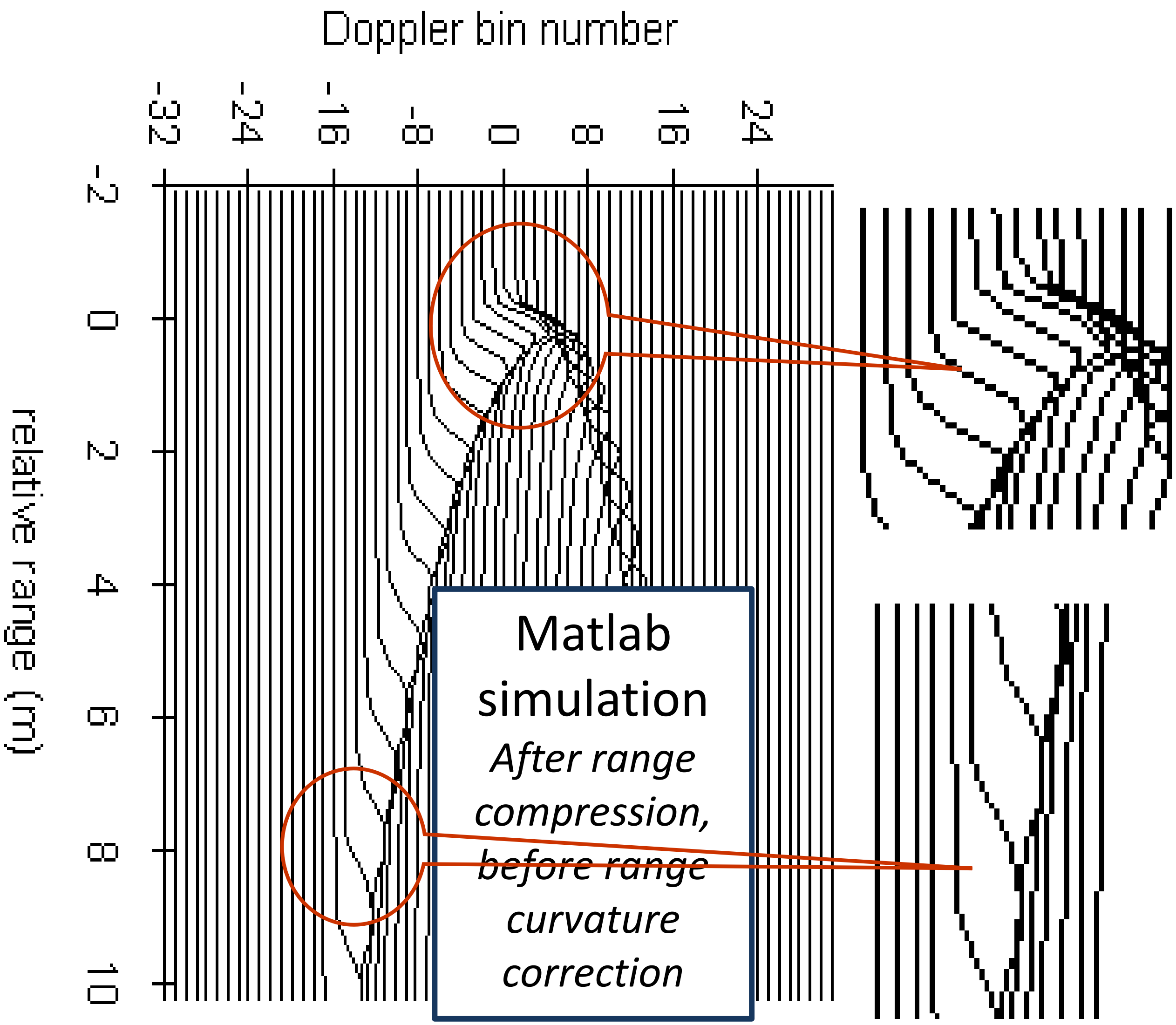
because….



waveform rise time sharpness decreases in (quadratic) proportion to distance from nadir

Useful Doppler Bins

Motivation for X_{Dop} to be small



$$N_{useful} \propto \frac{1}{X_{Dop}^2}$$

Walsh Upper Bound on Looks

Altitude (km)	717	1335	
	Looks per second		
$N_{\text{LRM/Walsh}}$	2100	1400	$\frac{2V_{SC}}{\lambda}\frac{2X_{PL}}{h}$
$N_{\text{unfocused, closed, }X\text{dop}}$	2700	1400	
$N_{\text{unfocused, (closed), Fresnel}}$	4700	3500	
$N_{\text{unfocused, open, }X\text{dop}}$	8100	4100	
$N_{\text{unfocused, open, Fresnel}}$	14000	10600	
$N_{\text{SAR, fully focused}}$	14800	14400	

Present

Prospects

Doppler Frequency Factor (~650 KHz)

Doppler frequency due to V_{SC}

$$\frac{2V_{SC}}{\lambda}\frac{2X_{PL}}{h}$$

	Altitude (km)	717	1335
		Looks per second	
Present	$N_{\text{LRM/Walsh}}$	2100	1400
	$N_{\text{unfocused, closed, }X\text{dop}}$	2700	1400
Prospects	$N_{\text{unfocused, (closed), Fresnel}}$	4700	3500
	$N_{\text{unfocused, open, }X\text{dop}}$	8100	4100
	$N_{\text{unfocused, open, Fresnel}}$	14000	10600
	$N_{\text{SAR, fully focused}}$	14800	14400

All "looks" are proportional to Doppler

Doppler frequency due to V_{SC}

	Altitude (km)	717	1335	
		Looks per second		
Present	$N_{\text{LRM/Walsh}}$	2100	1400	$\boxed{\dfrac{2V_{SC}}{\lambda}} \dfrac{2X_{PL}}{h}$
Present	$N_{\text{unfocused, closed, }X\text{dop}}$	2700	1400	$\dfrac{2V_{SC}}{\lambda} \dfrac{2n\rho_{rng}}{3X_{Dop}}$
Prospects	$N_{\text{unfocused, (closed), Fresnel}}$	4700	3500	$\dfrac{2V_{SC}}{\lambda} \dfrac{2n\rho_{rng}}{3\rho_{unf}}$
Prospects	$N_{\text{unfocused, open, }X\text{dop}}$	8100	4100	$\dfrac{2V_{SC}}{\lambda} \dfrac{2n\rho_{rng}}{X_{Dop}}$
Prospects	$N_{\text{unfocused, open, Fresnel}}$	14000	10600	$\dfrac{2V_{SC}}{\lambda} \dfrac{2n\rho_{rng}}{\rho_{unf}}$
Prospects	$N_{\text{SAR, fully focused}}$	14800	14400	$\dfrac{2V_{SC}}{\lambda} \dfrac{\lambda}{D} = \dfrac{V_{foot}}{\rho_1}$

BW_{Dop} also proportional to Antenna Beamwidth λ / D

Present

Prospects

Altitude (km)	717	1335	
	Looks per second		
$N_{\text{LRM/Walsh}}$	2100	1400	$\frac{2V_{SC}}{\lambda}\frac{2X_{PL}}{h}$
$N_{\text{unfocused, closed, }X\text{dop}}$	2700	1400	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{3X_{Dop}}$
$N_{\text{unfocused, (closed), Fresnel}}$	4700	3500	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{3\rho_{unf}}$
$N_{\text{unfocused, open, }X\text{dop}}$			$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{X_{Dop}}$
$N_{\text{unfocused, open, Fresnel}}$	14000	10600	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{\rho_{unf}}$
$N_{\text{SAR, fully focused}}$	14800	14400	$\boxed{\frac{2V_{SC}}{\lambda}\frac{\lambda}{D}} = \frac{V_{foot}}{\rho_1}$

Doppler bandwidth BW_{Dop}

BW_{Dop} also proportional to Antenna Beamwidth λ / D

		Altitude (km)	717	1335	
			Looks per second		
Present	$N_{\text{LRM/Walsh}}$		2100	1400	$\frac{2V_{SC}}{\lambda}\frac{2X_{PL}}{h}$
Present	$N_{\text{unfocused, closed, } X\text{dop}}$		2700	1400	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{3X_{Dop}}$
Prospects	$N_{\text{unfocused, (closed), Fresnel}}$		4700	3500	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{3\rho_{unf}}$
Prospects	$N_{\text{unfocused, open, } X\text{dop}}$				$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{X_{Dop}}$
Prospects	$N_{\text{unfocused, open, Fresnel}}$		14000	10600	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{\rho_{unf}}$
	$N_{\text{SAR, fully focused}}$		14800	14400	$\boxed{\frac{2V_{SC}}{\lambda}\frac{\lambda}{D}} = \frac{V_{foot}}{\rho_1}$

Doppler bandwidth BW_{Dop}

Maximum # looks/sec

BW_{Dop} also proportional to Antenna Beamwidth λ / D

Present

Prospects

Altitude (km)	717	1335	
	Looks per second		
$N_{\text{LRM/Walsh}}$	2100	1400	$\frac{2V_{SC}}{\lambda}\frac{2X_{PL}}{h}$
$N_{\text{unfocused, closed, }X\text{dop}}$	2700	1400	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{3X_{Dop}}$
$N_{\text{unfocused, (closed), Fresnel}}$	4700	3500	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{3\rho_{unf}}$
$N_{\text{unfocused}}$			$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{X_{Dop}}$
$N_{\text{unfocused, open, Fresnel}}$	14000	10600	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{\rho_{unf}}$
$N_{\text{SAR, fully focused}}$	14800	14400	$\frac{2V_{SC}}{\lambda}\frac{\lambda}{D} = \boxed{\frac{V_{foot}}{\rho_1}}$

"Resolution $\propto$ 1/bandwidth" where the scaling factor is V_{foot}

(*complex*) Nyquist $\geq 1 \times BW_{\text{Dop}}$

Altitude (km)	717	1335	
	Looks per second		
$N_{\text{LRM/Walsh}}$	2100	1400	$\frac{2V_{SC}}{\lambda}\frac{2X_{PL}}{h}$
$N_{\text{unfocused, closed, }X\text{dop}}$	2700	1400	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{3X_{Dop}}$
$N_{\text{unfocused, (closed), Fresnel}}$	4700	3500	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{3\rho_{unf}}$
$N_{\text{unfocused, open, }X\text{dop}}$	Doppler bandwidth BW_{Dop}		$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{X_{Dop}}$
Nyquist lower bound (Hz)	14000	10600	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{\rho_{unf}}$
$N_{\text{SAR, fully focused}}$	14800	14400	$\frac{2V_{SC}}{\lambda}\frac{\lambda}{D}=\frac{V_{foot}}{\rho_1}$

Present

Prospects

$(\textit{complex})\ \text{Nyquist} \geq 1 \times BW_{\text{Dop}}$

		Altitude (km)	717	1335	
			Looks per second		
Present		$N_{\text{LRM/Walsh}}$	2100	1400	$\frac{2V_{SC}}{\lambda}\frac{2X_{PL}}{h}$
Present		$N_{\text{unfocused, closed, } Xdop}$	2700	1400	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{3X_{Dop}}$
Prospects		$N_{\text{unfocused, (closed), Fresnel}}$	4700	3500	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{3\rho_{unf}}$
Prospects		$N_{\text{unfocused, open, } Xdop}$			$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{X_{Dop}}$
Prospects			14000	10600	$\frac{2V_{SC}}{\lambda}\frac{2n\rho_{rng}}{\rho_{unf}}$
Prospects		$N_{\text{SAR, fully focused}}$	14800	14400	$\frac{2V_{SC}}{\lambda}\frac{\lambda}{D}=\frac{V_{foot}}{\rho_1}$

Doppler bandwidth BW_{Dop}

Nyquist lower bound (Hz)

The SAR measurement *Uncertainty Principle*

$$\frac{\#\ of\ looks\ per\ \rho_{Az}}{resolution\ \rho_{Az}} \leq ¢\{Doppler\ bandwidth\}$$

* A. Papoulis, *Systems and Transforms with Applications to Optics*, McGraw-Hill, NY, 1968

* R. K. Raney, Radar Fundamentals, Technical Perspective, Chapter 2, Section 2-1.3, in *Manual of Remote Sensing, 3rd Ed, Principles and Applications of Imaging Radar*, F. M. Henderson and A. J. Lewis, Eds, Wiley, 1998.

The SAR measurement *Uncertainty Principle*

$$\frac{\#\ of\ looks\ per\ \rho_{Az}}{resolution\ \rho_{Az}} \leq \cent\{Doppler\ bandwidth\}$$

Why?

The SAR measurement *Uncertainty Principle*

$$\frac{\#\ of\ looks\ per\ \rho_{Az}}{resolution\ \rho_{Az}} \leq \ \cancel{c}\{Doppler\ bandwidth\ \}$$

Why?

(1) Because bandwidth determines the information "channel capacity" of the system…

(Claude Shannon, 1948)

…and that limited amount of information must support both looks and resolution.

The SAR measurement *Uncertainty Principle*

$$\frac{\#\ of\ looks\ per\ \rho_{Az}}{resolution\ \rho_{Az}} \leq \not{c}\left\{ Doppler\ bandwidth \right\}$$

Why?

(2) And… each look to be statistically-independent of all other looks must be generated from its own unique portion of the available bandwidth

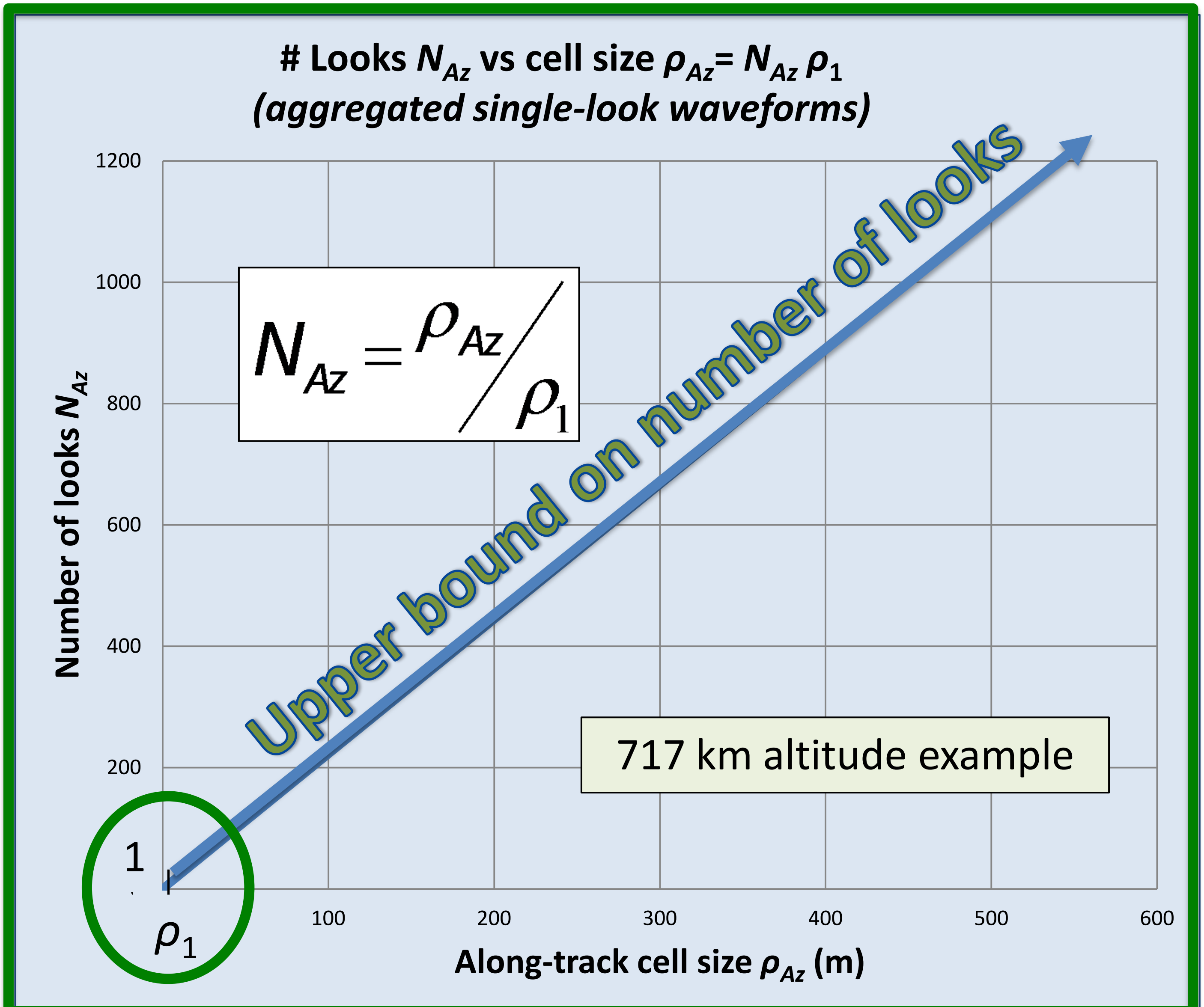
(a consequence of the Wiener-Khinchin theorem)

The SAR measurement *Uncertainty Principle*

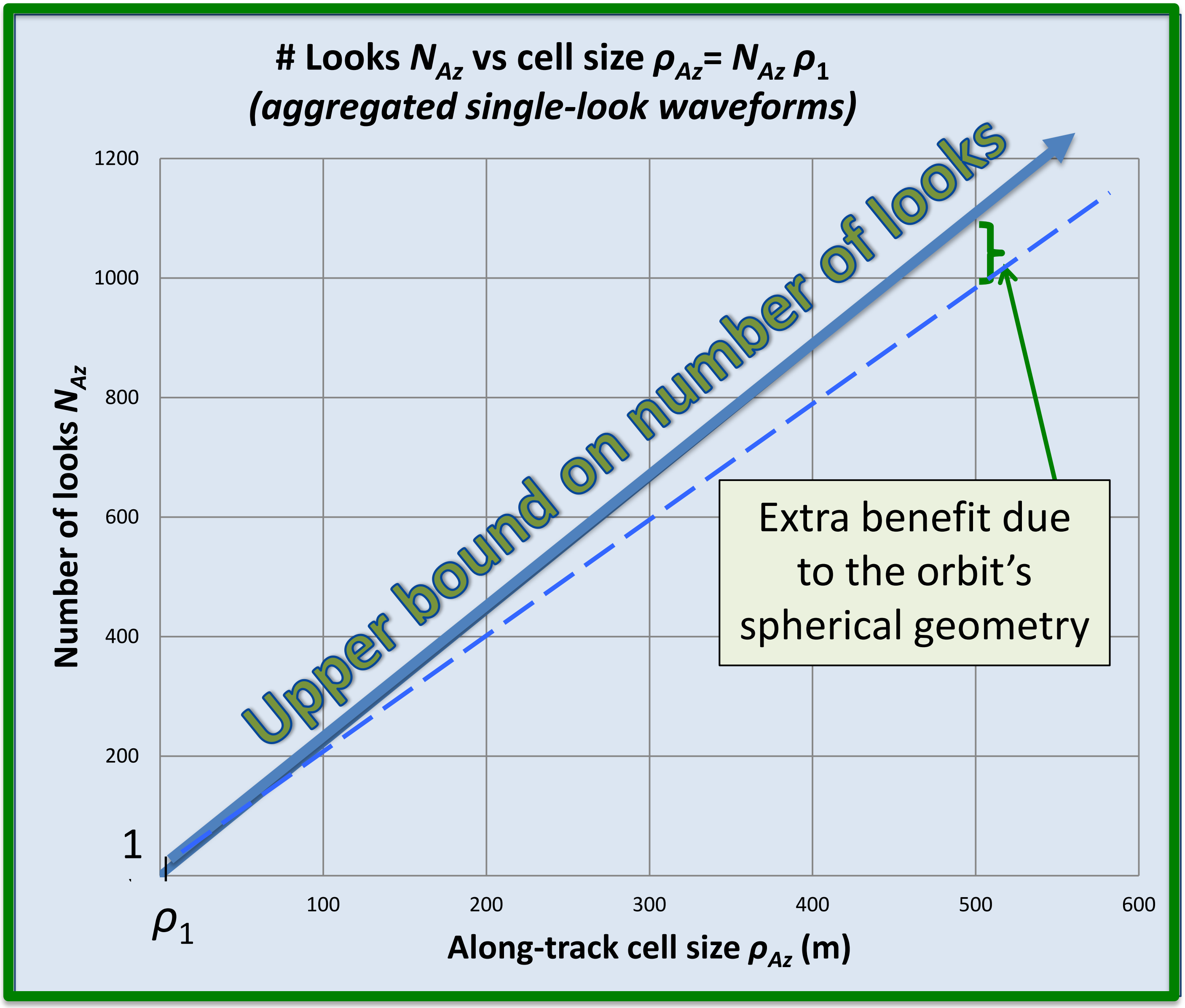
$$\frac{\#\ of\ looks\ per\ \rho_{Az}}{resolution\ \rho_{Az}} \leq ¢\{Doppler\ bandwidth\}$$

So,
Looks and Resolution
may be traded off

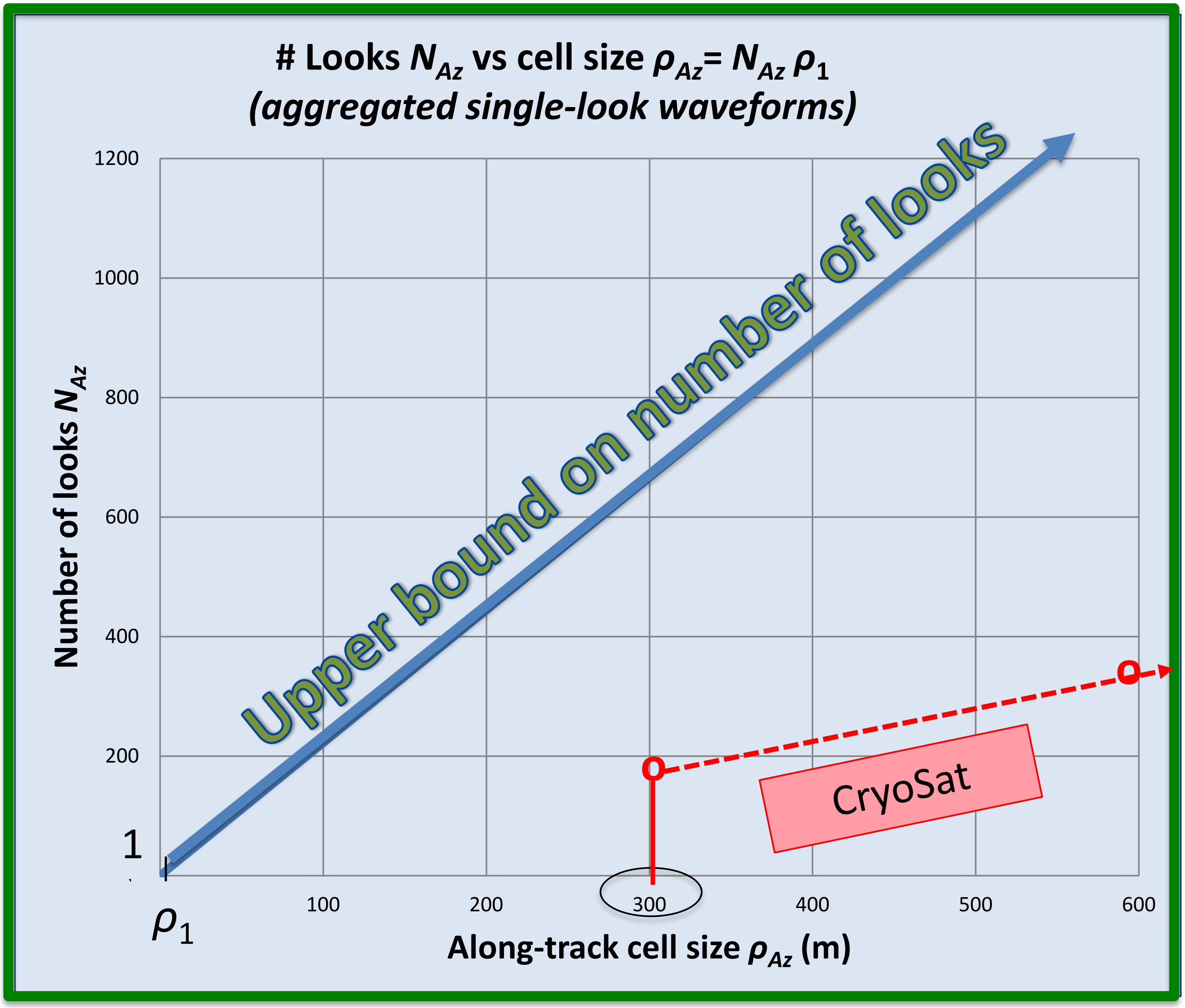
Looks N_{Az} *per* Azimuth Resolution ρ_{Az}



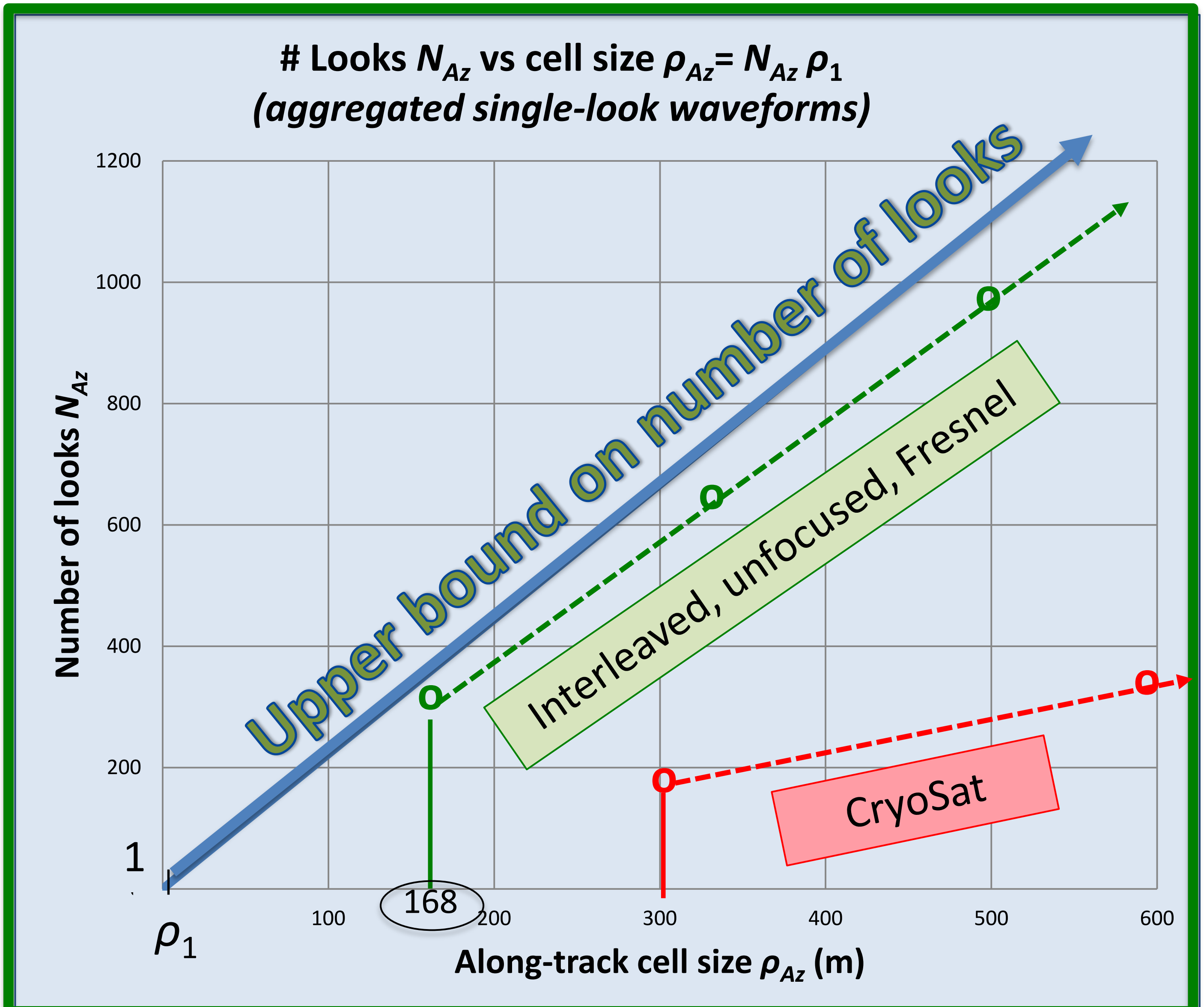
Looks N_{Az} *per* Azimuth Resolution ρ_{Az}



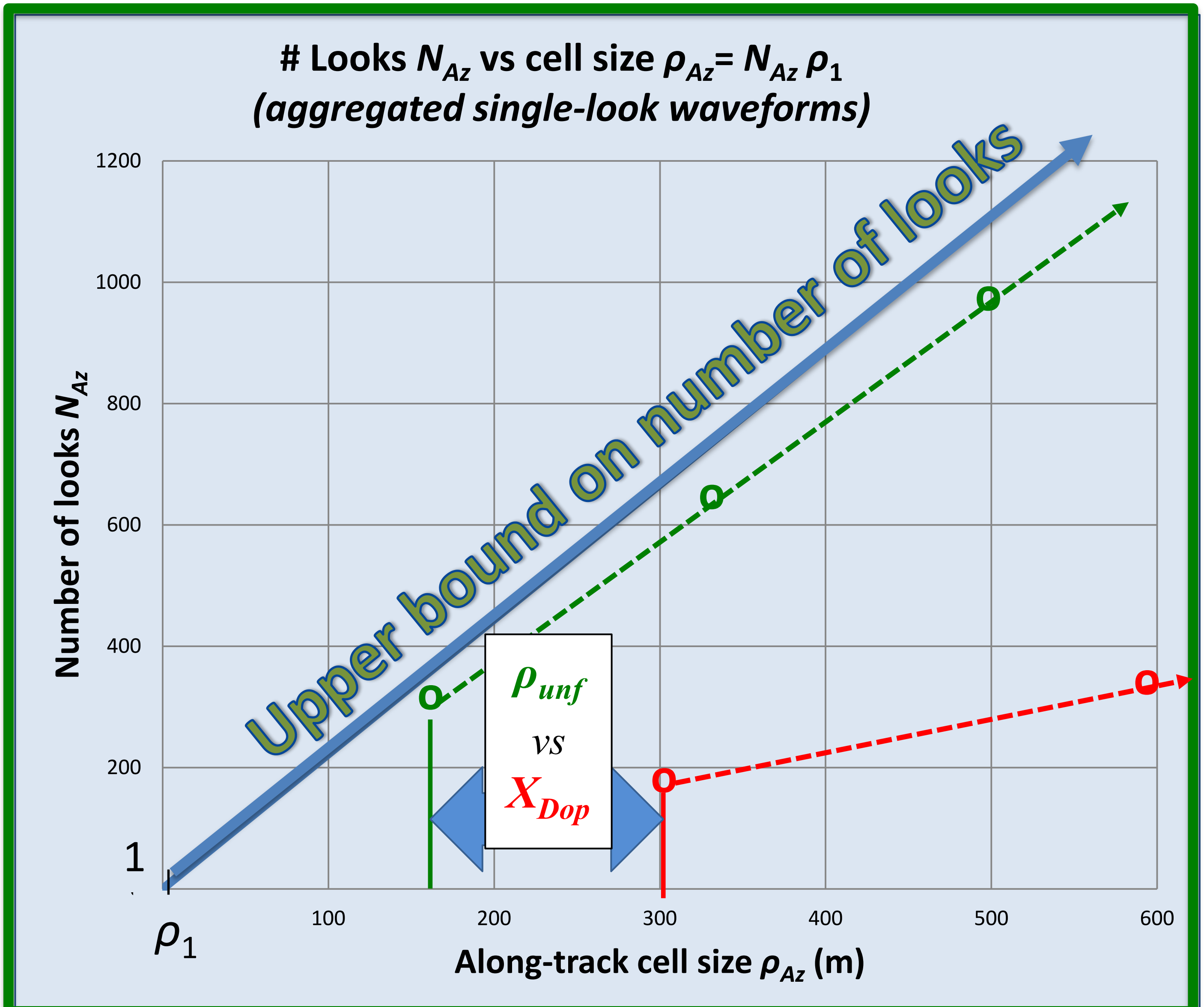
Looks: Present



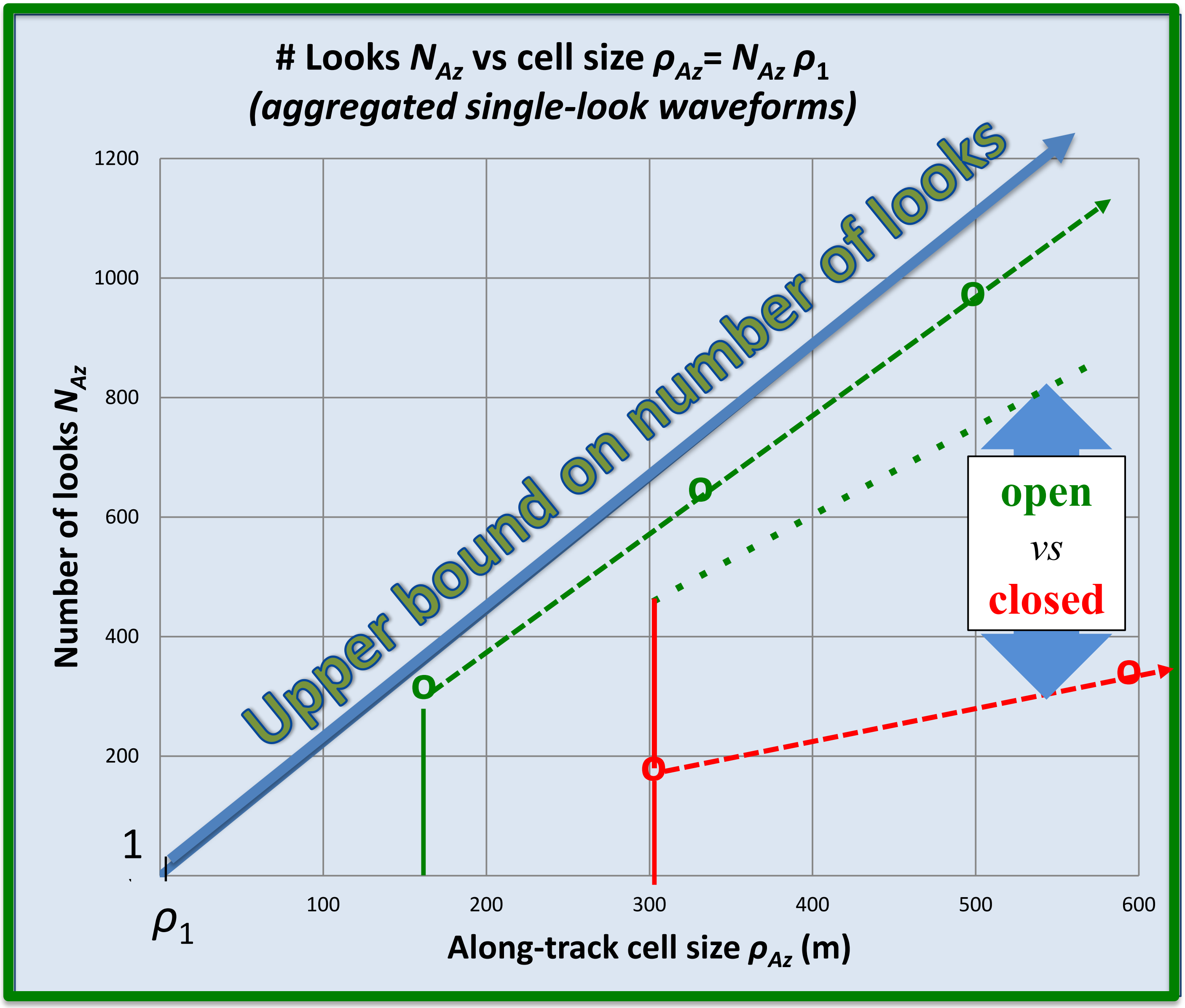
Looks: Present and Prospects



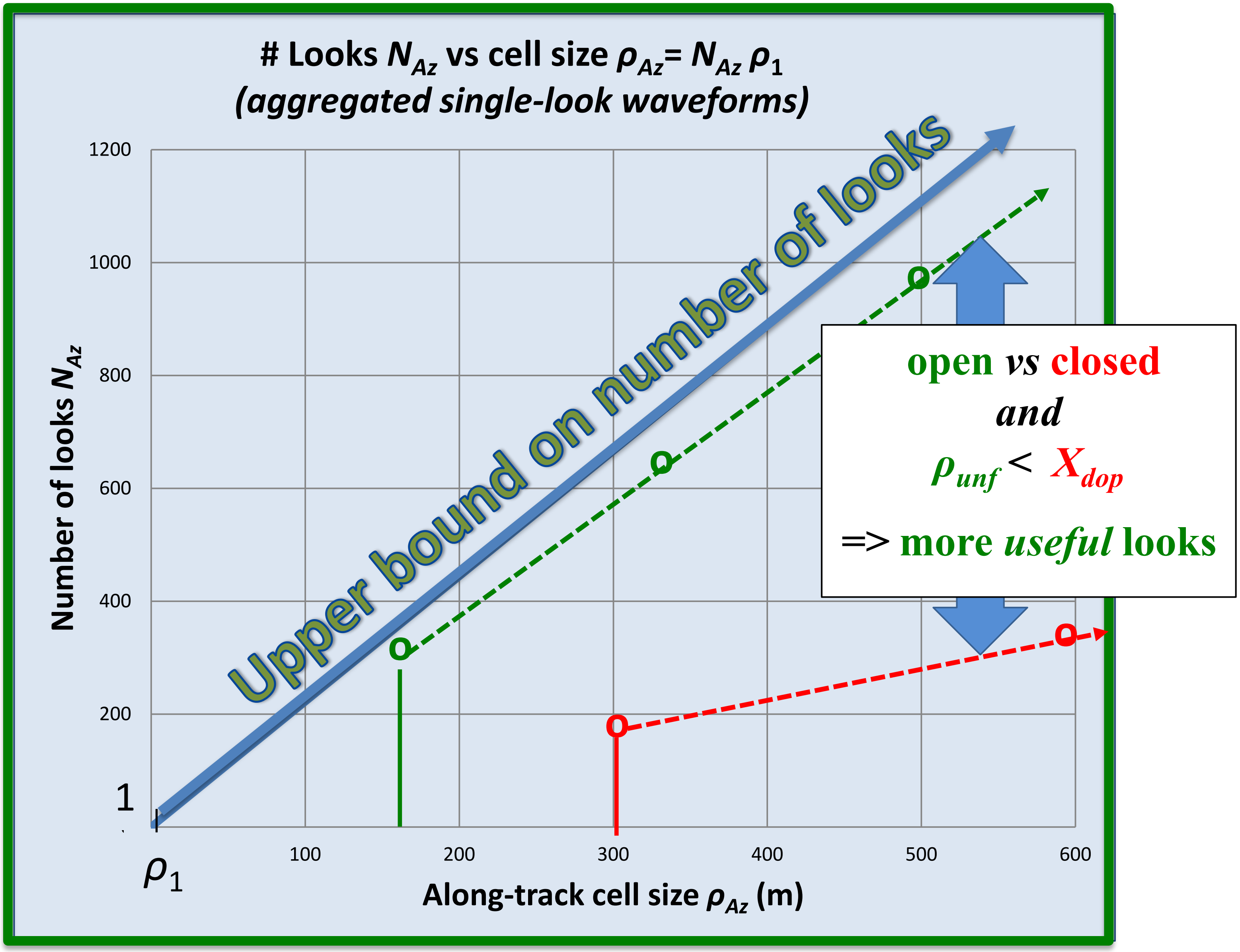
Looks and Resolution: *Unfocused*



Looks and Resolution: *Unfocused*

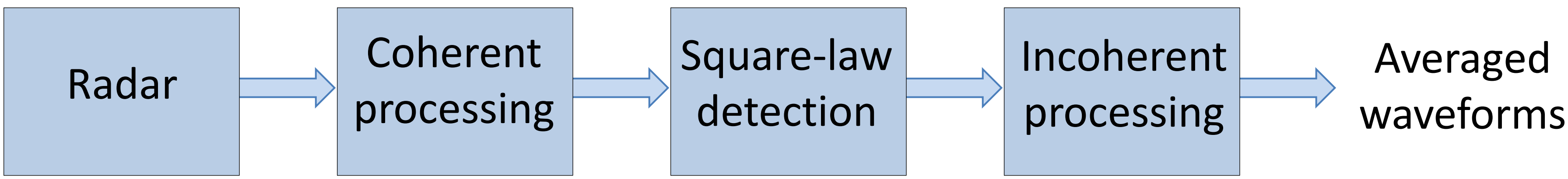


Looks and Resolution: *Unfocused*

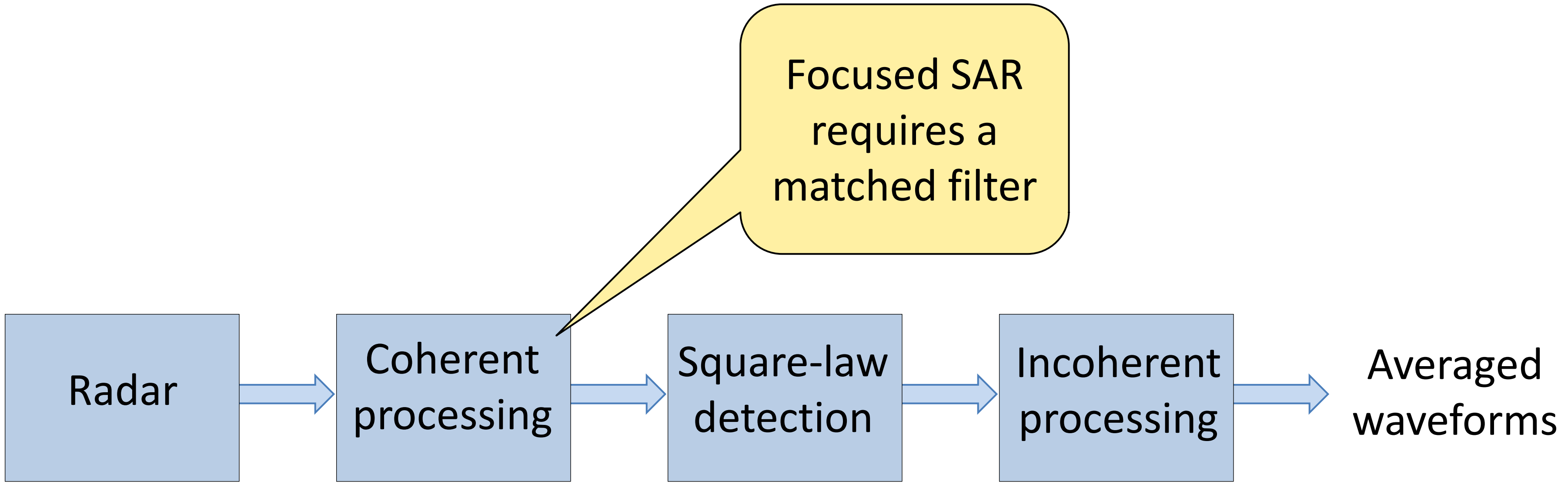


Top-Level System Model

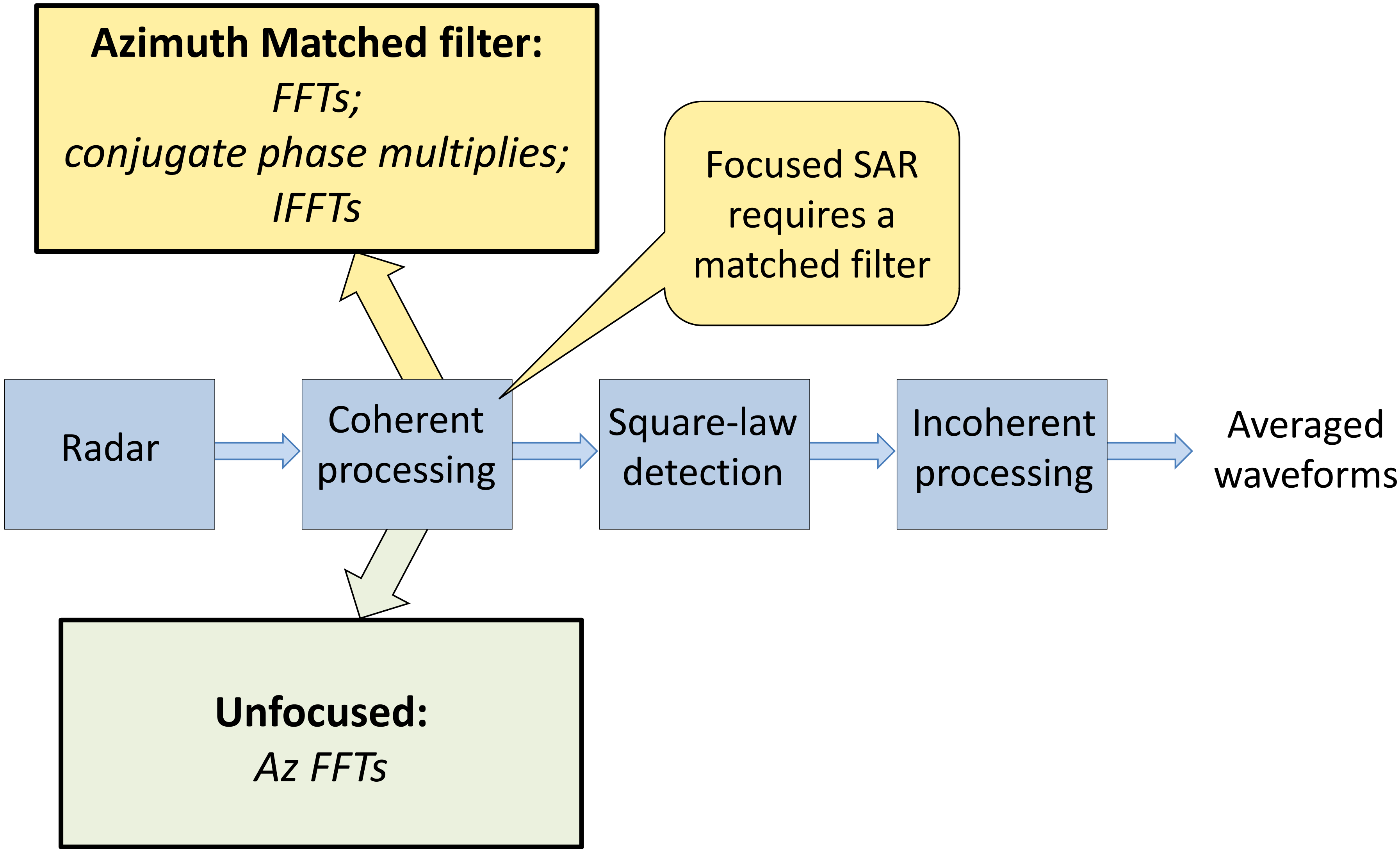
Interleaved (or open burst) mode



Issues (1)


Focused SAR requires a matched filter
Radar
Coherent processing
Square-law detection
Incoherent processing
Averaged waveforms

Issues (1)

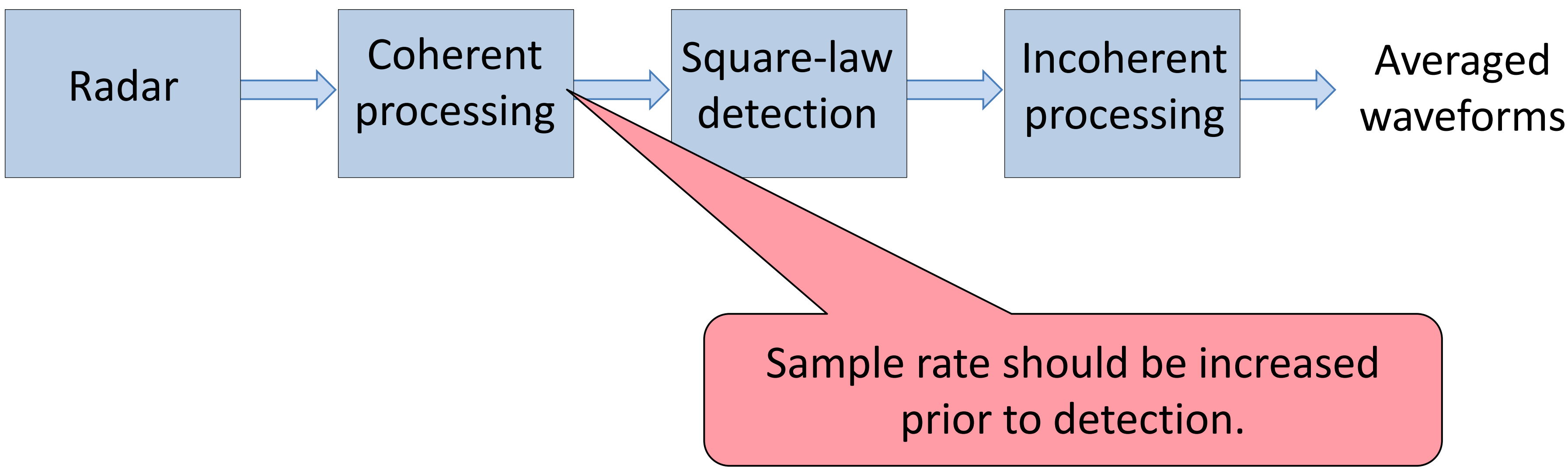

Azimuth Matched filter:
FFTs;
conjugate phase multiplies;
IFFTs
Focused SAR requires a matched filter
Radar
Coherent processing
Square-law detection
Incoherent processing
Averaged waveforms
Unfocused:
Az FFTs

Issues (2)

Interleaved *PRF* < (complex) Nyquist
hence….
Azimuth ambiguity management is essential

Radar → Coherent processing → Square-law detection → Incoherent processing → Averaged waveforms

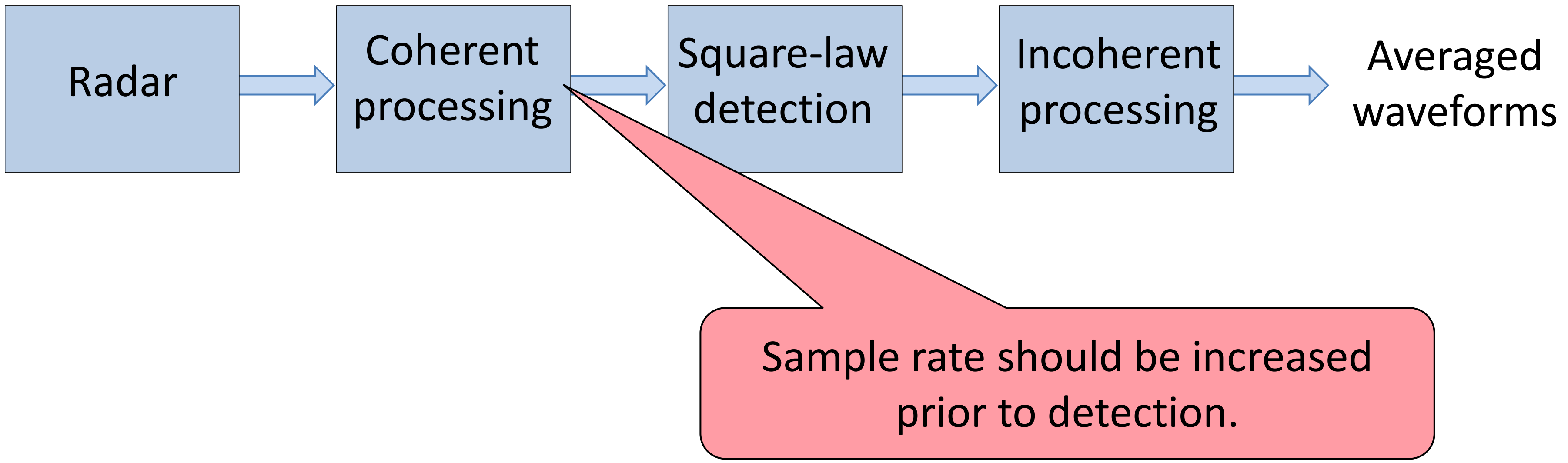
Issues (3)



Radar
Coherent processing
Square-law detection
Incoherent processing
Averaged waveforms
Sample rate should be increased prior to detection.

Issues (3)

- *Interleaved PRF (sample rate) is less than complex Nyquist* $\geq BW_{Dop}$

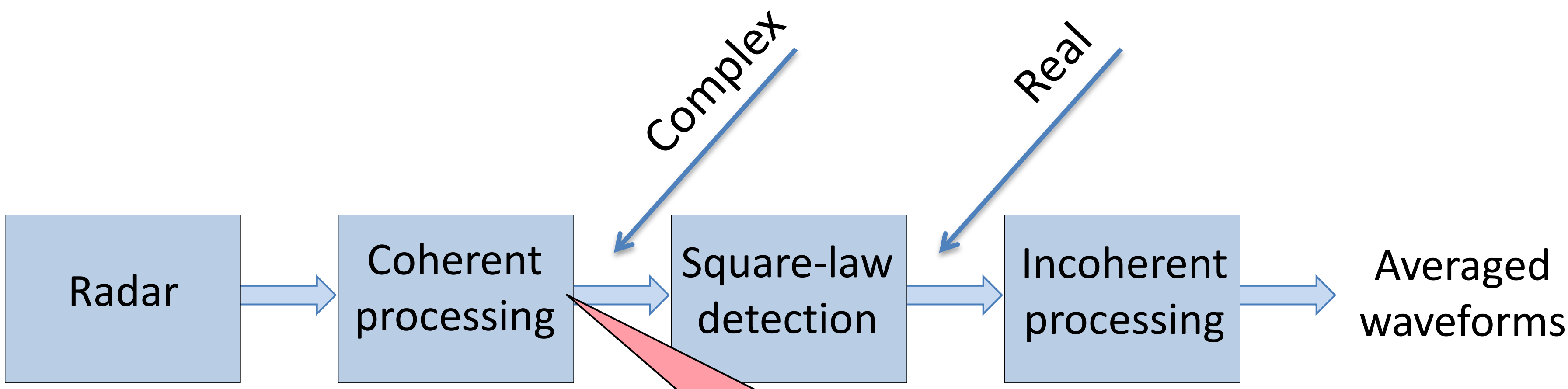


Issues (3)

- *Interleaved PRF (sample rate) is less than complex Nyquist ≥ BW_{Dop}*

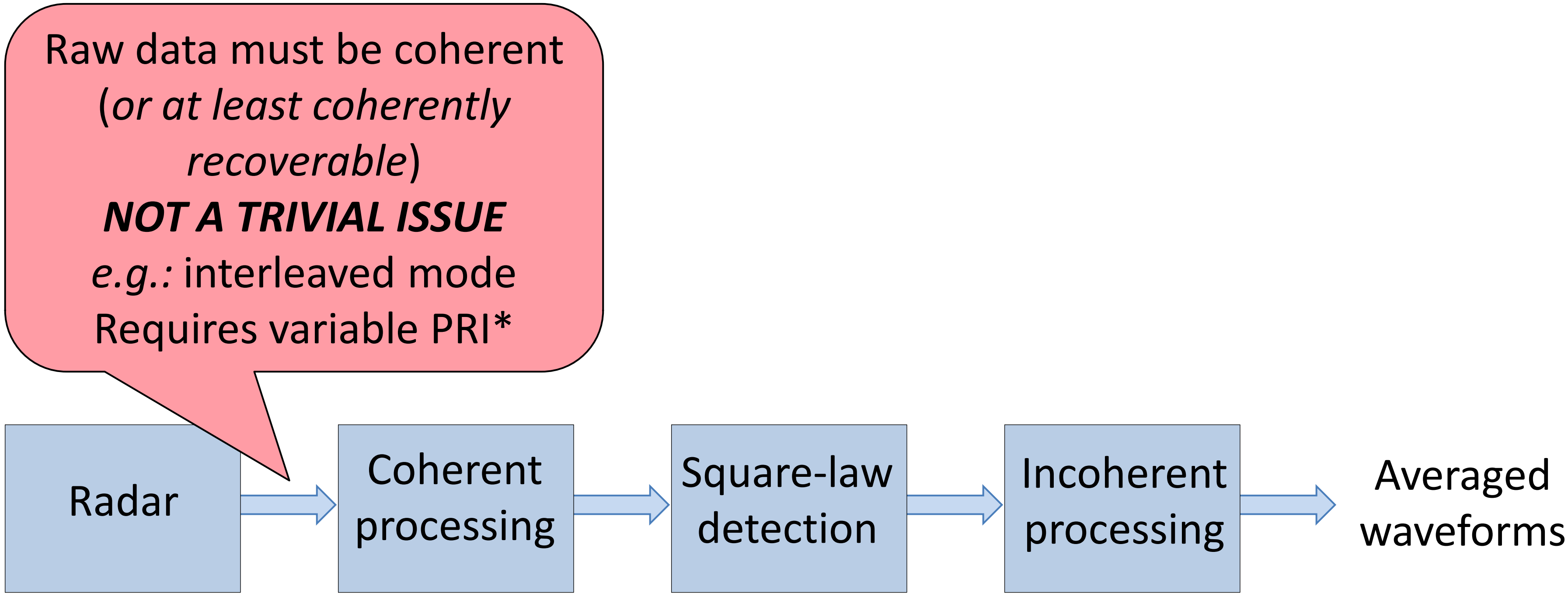
  AND

- *Real data Nyquist ≥ 2 BW_{Dop}*



Sample rate should be increased prior to detection.

Issues (4)



Raw data must be coherent
(*or at least coherently recoverable*)
NOT A TRIVIAL ISSUE
e.g.: interleaved mode
Requires variable PRI*
Radar
Coherent processing
Square-law detection
Incoherent processing
Averaged waveforms

Issues (4)

Raw data must be coherent (*or at least coherently recoverable*)

NOT A TRIVIAL ISSUE

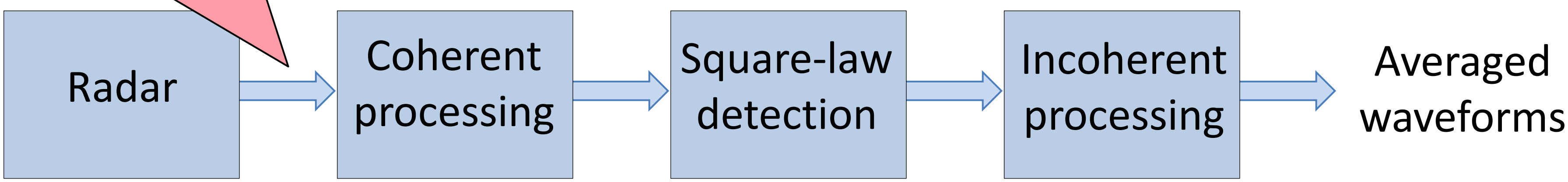
e.g.: interleaved mode

Requires variable PRI*

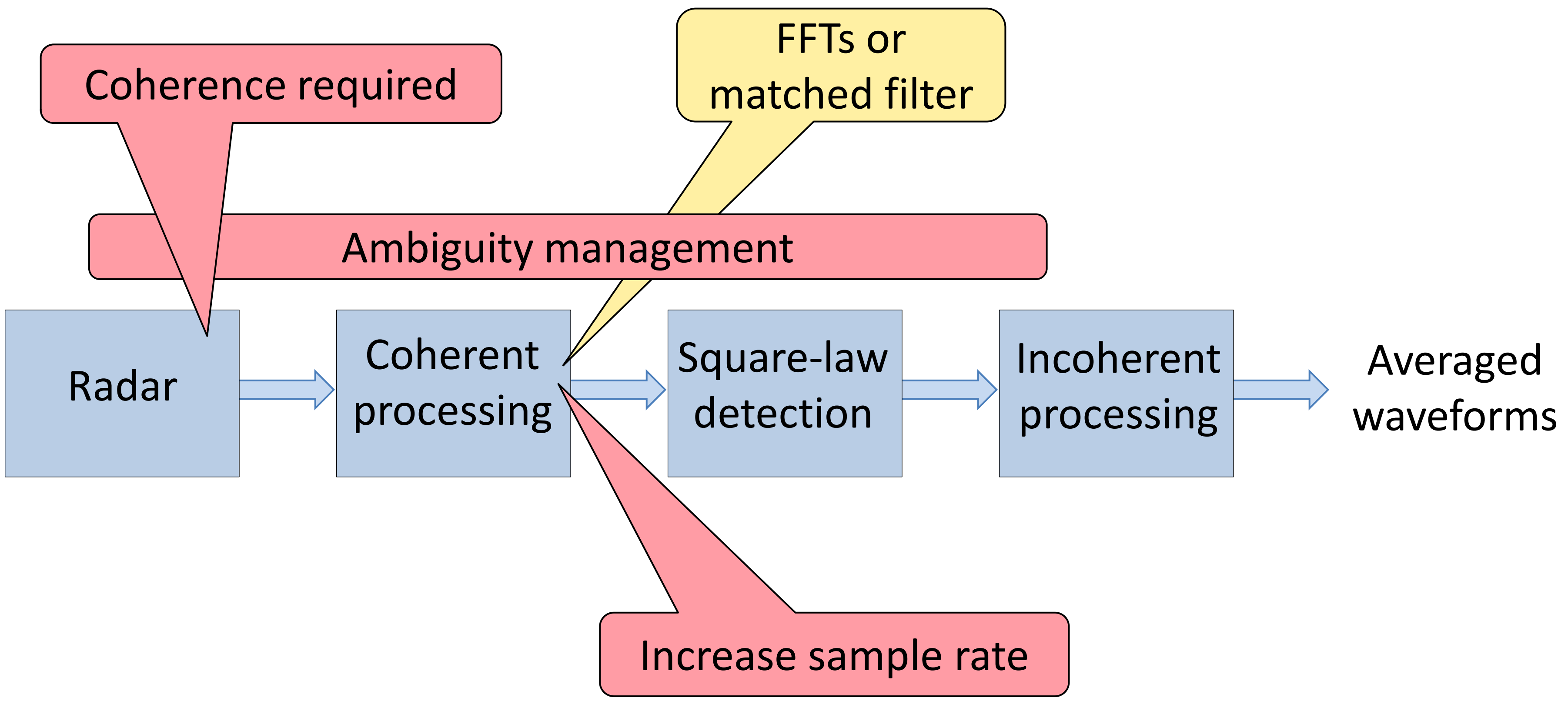
*Pulse Repetition Interval

The PRI must be adjusted to assure that the received data fall between the transmitted pulses for differing satellite heights.

Precedent: TOPEX (1992)

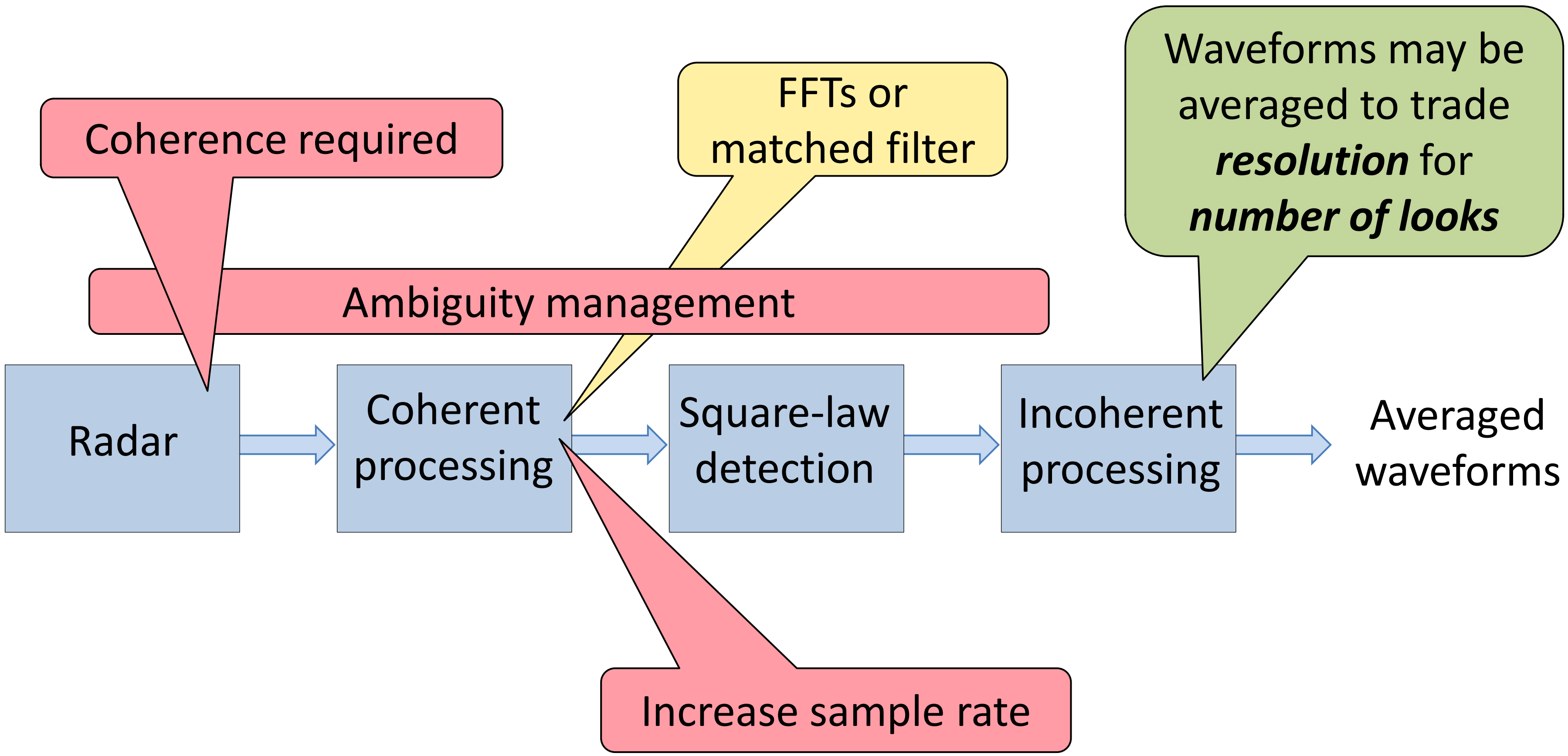


Issues and ➔ ➔ ➔ ➔



Coherence required
FFTs or matched filter
Ambiguity management
Radar
Coherent processing
Square-law detection
Incoherent processing
Averaged waveforms
Increase sample rate

Issues and a Useful Looks Methodology



Lessons Learned: Prospects

- ***Fully focused SAR mode is necessary and sufficient to establish the upper bound on number of looks per ρ_{Az}***

Lessons Learned: Prospects

- *Fully focused SAR mode is necessary and sufficient to establish the upper bound on number of looks per ρ_{Az}*
- *Unfocused / DDA processing of interleaved data can achieve near-maximum number of looks*

Lessons Learned: Prospects

- Fully focused SAR mode is necessary and sufficient to establish the upper bound on number of looks per ρ_{Az}
- Unfocused / DDA processing of interleaved data can achieve near-maximum number of looks
- Unfocused system design should assure $X_{Dop} \approx \rho_{unf}$

Lessons Learned: Prospects

- *Fully focused SAR mode is necessary and sufficient to establish the upper bound on number of looks per ρ_{Az}*
- *Unfocused / DDA processing of interleaved data can achieve near-maximum number of looks*
- *Unfocused system design should assure $X_{Dop} \approx \rho_{unf}$*
- *Summing fine-resolution (power) waveforms from adjacent cells expands along-track resolution to a desired level, while capturing the maximum available number of looks for that resolution*

Lessons Learned: Prospects

- *Fully focused SAR mode is necessary and sufficient to establish the upper bound on number of looks per ρ_{Az}*
- *Unfocused / DDA processing of interleaved data can achieve near-maximum number of looks*
- *Unfocused system design should assure $X_{Dop} \approx \rho_{unf}$*
- *Summing fine-resolution (power) waveforms from adjacent cells expands along-track resolution to a desired level, while capturing the maximum available number of looks for that resolution*
- *Ambiguity management essential when prf < Nyquist*

Lessons Learned: Prospects

- Fully focused SAR mode is necessary and sufficient to establish the upper bound on number of looks per ρ_{Az}
- Unfocused / DDA processing of interleaved data can achieve near-maximum number of looks
- Unfocused system design should assure $\mathbf{X_{Dop}} \approx \rho_{unf}$
- Summing fine-resolution (power) waveforms from adjacent cells expands along-track resolution to a desired level, while capturing the maximum available number of looks for that resolution
- Ambiguity management essential when prf < Nyquist
- Radar: raw data must support coherent processing

Lessons Learned: Prospects

- *Fully focused SAR mode is necessary and sufficient to establish the upper bound on number of looks per ρ_{Az}*
- *Unfocused / DDA processing of interleaved data can achieve near-maximum number of looks*
- *Unfocused system design should assure $X_{Dop} \approx \rho_{unf}$*
- *Summing fine-resolution (power) waveforms from adjacent cells expands along-track resolution to a desired level, while capturing the maximum available number of looks for that resolution*
- *Ambiguity management essential when prf < Nyquist*
- *Radar: raw data must support coherent processing*
- *Processing: should increase sample rate before $|x|^2$*

. . . and always keep in mind . . .


LOOKS !!!
La Rochelle – France – 31 Oct. 2016
SAR altimetry workshop

SAR Altimetry References (Selected)
R. K. Raney

SAR-mode altimetry precedents

Since the mid-1980s there has been a growing interest in radar altimeter innovations that would improve their reliability and accuracy over terrain and continental ice sheets. The synthetic aperture (or, better, synthesized aperture) technique that is central to the success of SAR imaging systems seemed attractive, as should be apparent from the following studies:

Aleksandrov, Y. N., A. T. Bazilenvsk, Y.N., V. A. Kotelnikov, G. M. Petrov, O. N. Rzhiga, and A. I. Sidorenko, "A planet rediscovered: Results of Venus radar imaging from the Venera 15 and Venera 16 spacecraft", *Sov. Sci. Rev. E. Astrophys. Space Phys.*, 6, Part 1:61-101, 1988.

The Soviets, who had been the first to apply radar altimetry from orbit at Venus (Venera-8, 1972), embarked a more sophisticated altimeter on their SAR imaging Veneras (1983). Those altimeters were the first in orbit designed to support (digital) SAR processing techniques utilizing Doppler processing techniques.

Griffiths, H. and B. Purseyyed, *A Study of Advanced Radar Altimeter Techniques,* ESA Contract report 7088/87/NL/JG(SC), ESTEC, Noordwijk, The Netherlands, 1988.

The study group included C. G. Rapley, D. J. Wingham, F. Li, and D. Maccoll. The conclusions made recommendations in favor of SAR style altimeters for land and continental ice applications, but deferred the looks topic (number of statistically independent samples) to later consideration.

Griffiths, H.D., "Synthetic Aperture Processing for Full-Deramp Radar Altimeters", *Electronic Lett.*, 24, 371-373, 1988.

Hugh had included a brief discussion of SAR-style altimetry in his PhD dissertation. Subsequent considerations of that approach in Europe were influenced by his early work.

Purseyyed, B. and H. D. Griffiths, "A Synthetic Aperture Altimeter", *Proceedings IEEE International Geoscience and Remote Sensing Symposium, Edinburgh,* ESA SP-284, 1988.

This article promoted an elemental form of SAR-style processing—unfocused—and observed that the SAR approach to along-track beam sharpening was compatible with the full-deramp (stretch) method that had been incorporated in satellite altimeters since GEOS-3 (1975). Due primarily to processing burden constraints, the paper suggested a single-beam implementation which required relatively simple integrations for Doppler beam-sharpening. Such an approach severely limits the number of available statistically-independent looks—to one—which would render the resulting product to be nearly useless. Previously the Doppler beam-sharpening technique had been tried on side-looking real-aperture imaging radars (by Raytheon and other US radar companies) with disappointing results caused by high speckle-to-signal ratio.

Rapley, C. G., H. D. Griffiths, P. A. Berry, Eds, *Proceedings of the consultative meeting on imaging altimeter requirements and techniques,* ESA MSSL/RSG/90.01, 1990.

This two-day meeting produced several significant studies aimed at SAR-enhanced radar altimetry to improve surface elevation accuracy, primarily over ice and terrain.

Barbarossa, S. and G. Picardi, "The synthetic aperture concept applied to altimetry: Surface and sub-surface imaging", in *Proceedings of the consultative meeting on imaging altimeter requirements and techniques*, MSSL/RSG 90.01, 1990.

This article is a good example of the products from the 1990 consultative meeting, and highlights the logical link between altimeters and sounders.

Ford, P. G., and G. H. Pettengill, “Venus topography and kilometer-scale slopes”. *J. Geophys. Res*., 97(E8):13103-13114, 1992.

According to the historical sketch outlined to me by Peter Ford, the Soviet approach to SAR-enhanced radar altimetry was transferred to the then nascent Magellan mission in the mid-1980s, in exchange for data access and professional cooperation between the US and Soviet planetary radar programs. The altimeter on Magellan operated in closed burst mode, from which its data could be processed either as conventional noncoherent altimetry, or in delay/Doppler enhanced mode. Peter did the altimeter data reduction on his desk-top computer, which in those days required many weeks of dedicated processing.

Raney, R. K., “A delay/Doppler radar altimeter for ice sheet monitoring”, in *Proceedings of International Geoscience and Remote Sensing Symposium IGARSS 1995*. Florence, Italy: IEEE, 1995 pp. 862-864.

This was the first public disclosure of the “delay/Doppler” project at JHU/APL, and was one of the initiating factors for two subsequent European studies of the technique, which at the time was known by the acronym HSRRA – High Spatial-Resolution Radar Altimeter. The approach was motivated by the demands of continental ice sheet elevation requirements, as well as a means of generating more looks per unit time than conventional altimeters. The concept was implemented by JHU/APL for airborne demonstrations. The resulting D2P altimeter (supported by a NASA Instrument Incubator grant) was the first operational prototype of the architecture that eventually went to space as CryoSat.

Phalippou, L., Feasibility study of HSRRA for ESA, ESA/ESTEC 12178/96/SB(SC), 1997.

This was one of the two studies in Europe that were prompted by Duncan Wingham’s exposure to the combined delay/Doppler and cross-track interferometric altimeter concept through his membership on the science team for JHU/APL’s ESSP NASA proposal (1996).

R. K. Raney, "The delay Doppler radar altimeter," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 36, pp. 1578-1588, 1998.

Expanding on a previous conference paper (IGARSS’95), this was the first journal publication of a practical implementation of a multi-look unfocused synthetic aperture radar approach to oceanic altimetry. In this method, the cross-track impulse responses for all beams are pulse-limited. In contrast, in the along-track dimension, the delay-Doppler algorithm generates many “mini-altimeters” in parallel. Each along-track impulse response is beam-limited, and each such beam is pointed at a unique and known off-nadir angle. Both the beam-limited widths and pointing angles are established by Fourier transforms aver blocks of received data. A major feature of this approach is that there are *substantially more statistically-independent looks than from a conventional altimeter, expressed by the Walsh upper bound.*

Picardi, G., R. Seu, and S. Sorge, "Extensive non-coherent averaging in Doppler beam sharpened space-borne radar altimeters," in *Proc. IEEE International Geoscience and Remote Sensing Symposium*, Seattle, WA, 2643–2645, 1998.

This paper is an independent validation of the claim that SAR-inspired processing increases the available number of looks in comparison to conventional non-coherent altimetry.

Leuschen, C. J., and R. K. Raney, "Initial results of data collected by the APL D2P radar altimeter over land and sea ice", *Johns Hopkins APL Technical Digest,* 26(2): 114-122, 2005.

This paper describes simultaneous laser and radar altimetric measurements over land and sea ice. Several missions were flown, in the Arctic and sub-Arctic as part of the early airborne demonstration phase of the CryoSat mission, and in Antarctica as part of the first Ice Bridge program of NASA.

https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/cryosat (2010)

https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-3 (2016)

Aside: Radar sounding

Although seemingly different from each other, radar sounders and altimeters share essential characteristics that have motivated SAR-style processing enhancements. Both are downward-looking. Their respective data products are vertical profiles of backscatter reflectivity. In the case of sounders, the main objectives are to eliminate the usual extensive hyperbolic signature of embedded reflectors, to sharpen the along-track footprint resolution in situ, to reduce clutter, and to increase the signal-to-speckle ratio (through increased averaging). Notable examples of relevant radar sounders that apply SAR-inspired architecture and design include the following:

L. J. Porcello, L. J., R. L. Jordan, J. S. Zelenka, G. F. Adams, R. J. Phillips, W. E. Brown, S. H. Ward, P. L. Jackson, "The Apollo lunar sounder radar system", *Proceedings of the IEEE*, 62(6):769-783, 1974.

Yes, a 1974 publication, about the radar sounder aboard Apollo 17 (1972), the final US manned mission to the Moon. The payload included the ALSE instrument, the first SAR-mode radar sounder in orbit. Its architecture was similar to airborne side-looking synthetic aperture radars of the time, recording its data on optical film, later to be processed in a specialized coherent optical computer. For ALSE, the film canister's retrieval required an EVA by an astronaut (Ron Evans) during the return flight from the Moon. Prior to the lunar mission a prototype instrument had been tested over Greenland from a KC-135 aircraft.

Raju, G. and R. K. Moore, "A matched-filter technique for removing hyperbolic effects due to point scatterers: simulation and application on Antarctic radar data", *IEEE Trans on Geoscience and Remote Sensing*, 28(4):726-729, 1990.

Embedded point scatterers generate inverted hyperbolic traces (familiar to SAR folks as range curvature) in conventional radar sounder data, due to the decreasing then increasing range to the radar as it passes by. At the time, geophysicists used the shape of those hyperbolae to estimate the dielectric constant of the intervening material (usually ice), but instrument engineers wanted to eliminate the unwanted tails. SAR theorists wanted to use the phase structure in the tails to focus the returns, which required matched phase processing and correction of severe range curvature. Fully-focused radar altimeter data processing faces similar challenges.

Picardi, G., S. Sorge ; R. Seu ; J. J. Plaut ; W. T. K. Johnson ; R. L. Jordan ; D. A. Gurnett ; R. Orosei ; L. Borgarelli ; G. Braconi ; C. Zelli ; E. Zampolini, "The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS): concept and performance", *Proceedings IEEE International Geoscience and Remote Sensing Symposium,* 5:2674 – 2677, 1999.

MARSIS, and its follow-on SHARAD, were successful, thanks to extensive programs and individual efforts in a bilateral arrangement between Italy and the US (lead by JPL). Both sounders included modes that employed SAR techniques, although of limited capability due primarily to data volume, rate, and communication constraints. This heritage has served as an excellent foundation for the current bilateral design and implementation program on a radar sounder for Europa.

Leuschen, C. and R. Plumb, "A matched filter approach to wave migration", *J. of Applied Geophysics,* 43(2):271-280, 2000.

Both Leuschen and Legarsky (see below) wrote their PhD dissertations centered on focused SAR methodology adapted to radar sounding. Carl, then at APL as a post-doc fellow, was the lead engineer for the design of the D2P airborne altimeter that became the prototype for CryoSat.

Legarsky, J. J., S. P. Gogineni, and T. L. Akins, "Focused synthetic aperture radar processing of ice-sounder data collected over the Greenland Ice Sheet", *IEEE Trans Geoscience and Remote Sensing*, 39(10): 2109-2117, 2001.

This is the condensed version of Justin's dissertation. His was the first serious and reasonably successful attempt at fully-focused processing for airborne radar sounder data.

Peters, M. E., D. D. Blankenship, S. P. Carter, S. D. Kempf, D. A. Young, and J. W. Holt, "Along-track focusing of airborne radar sounding data from West Antarctica for improving basal reflection analysis and layer detection", *IEEE Transactions on Geoscience and Remote Sensing*, 45(9):2725-2736, 2007.

Don Blankenship (U. Texas, Austin) has for decades lead a major Antarctic ice-sounding survey program. He and his students have taken the airborne radar sounder originally developed by Preben Gudmandsen (Denmark) to new standards of performance, including the fully focused SAR mode.

Dall, J., S. S. Kristensen, V. Krozer, C. C. Hernandez, J. Vidkjær, A. Kusk, J. Balling, N. Skou, S. S. Sobjærg, E. L. Christensen, "ESA'S POLarimetric Airborne Radar Ice Sounder (POLARIS): design and first results", *IET Radar, Sonar, and Navigation*, 4(3):488-496, 2010.

This is the first radar sounder to include polarimetrics as well as SAR processing. It follows a long tradition of radar sounding innovation in Denmark.

Towards fully-focused SAR altimetry

The promise of further improvements in performance and steadily increasing digital processing capabilities, reinforced by growing interest by users in such improvements, has motivated significant progress in radar altimetry instrumentation and processing. Whereas fully focused (along-track) SAR altimetry was once deemed to be not practical, in the near future it is likely to become an operational reality. Notable milestones in that evolution include:

D. J. Wingham, et al., "CryoSat: A Mission to Determine Fluctuations in the Mass of the Earth's Land and Marine Ice Fields," University College, London, UK, Proposal to the European Space Agency, October 1998.

Although such an instrument previously had been proposed in the first ESSP competition (1996), at the time NASA passed up the opportunity. The proposal to ESA, which featured essentially the same instrument concept, was based on an excellent science rationale, written by Duncan. It was selected to become the first Earth Explorer mission.

J. R. Jensen and R. K. Raney, "Delay Doppler radar altimeter: Better measurement precision," in *Proceedings IEEE Geoscience and Remote Sensing Symposium IGARSS'98*. Seattle, WA: IEEE, 1998, pp. 2011-2013.

Delay-Doppler generates more statistically-independent waveforms, hence these when summed render the standard deviation of the retrieved parameters to be smaller than those available from any conventional altimeter. This paper summarizes the results of simulations that verify the theoretical predictions.

Phalippou, L., P. Piau, D. J. Wingham, and C. Mavrocordatos, "High spatial resolution radar altimeter for ocean and ice-sheet monitoring", in *Proceedings IEEE Geoscience and Remote Sensing Symposium IGARSS'98*. Seattle, WA: IEEE, 1998, pp. 2020-2022.

This paper notes further progress towards an unfocused SAR mode altimeter. Simulations essentially agree with the first published predictions. The conclusions note that the available number of looks, although a "key issue", deserves further investigation.

R. K. Raney, "CryoSat SAR-mode looks revisited," *Proceedings, ESA Living Planet Symposium*, Bergen Norway, 28 June – 02 July 2010, subsequently published in *IEEE Geoscience and Remote Sensing Letters*, vol. 9, pp. 393-397, 2012.

Open publication of the central points in the 2010 Bergan paper, including in particular the first observation that the closed burst paradigm limits the available measurements to only about 1/3 of those possible through continuous along-track data collection. The paper also offers the basic parameters of an improved design approach. This idea leads to an interleaved mode, for which the PRF is much lower than the Nyquist lower bound, yet much higher than the Walsh upper bound, thus "breaking out of the box" of both conventional synthetic aperture radar and conventional radar altimetry.

R. K. Raney, "Maximizing the intrinsic precision of radar altimetric measurements," *IEEE Geoscience and Remote Sensing Letters,* Vol. 10, No. 5, pp. 1171-1174, 2013.

This is the complete version of a conference paper, including the "Vision" section (arguing for simultaneity of LRM and SAR modes) that was presented from the floor during the closing plenary discussion at the 2012 Venice meeting. The principal conclusion is that a fully interleaved (open burst) approach maximizes measurement precision, while accommodating full compatibility with historical conventional altimetric data records.

C. Gommenginger, C. Martin-Puig, L. Amarouche, and R. K. Raney,
Review of State of Knowledge for SAR Altimetry over Ocean, Version 2.2, EUMETSAT, EUM/RSP/REP/ 14/74930421, November 2013.
https://www.dropbox.com/s/u3mlmkzjmgv243r/SARAltimetry_EUMETSAT_JasonCS_review_v2.2.pdf

This report defends the proposition that the SAR interleaved mode is essential for future radar altimeters. It is the only method that substantially improves measurement precision, while assuring continuity between the SAR mode(s) aboard Jason-CS/Sentinel-6, and data from all other prior (conventional and burst mode delay/Doppler) altimeter missions. The central argument is that adopting the original closed-burst approach on Sentinel-6 would have compromised the continuity of the 25-year sea level time series.

SAR Processing

In contrast to unfocused processing, for which along-track Fourier transform (coherent) integrations suffice, fully-focused processing requires that the phase structure of the received signals be known and "matched". The standard way for most SAR implementations is to perform azimuth Fourier transforms to express the signal data in the Doppler frequency domain. The major advantage of this step is that the frequency constituents of all of the signals are single-valued. Hence, the phase modulation across the full bandwidth can be neutralized through complex multiplication by a conjugate phase function. After that "matched filter" complex multiply, the resulting signal ensemble consists of simple CW waveforms. Subsequently, application of IFFTs collapse each CW constituent to a sharp (focused) point at an azimuth location dictated by their individual frequency. (This last step in principle is the same as is routinely done in the range direction of conventional radar altimetry.) Effective complex operations in the azimuth direction require that the phase structure be known, and that the specifics of that structure have no residual distortions caused by the radar. In short, the signal data must support coherent processing over the bandwidth (and time duration) of the intended integrations.

Carrara, W. G., R. S. Goodman, and R. M. Majewski, *Spotlight Synthetic Aperture Radar*, Artech House, Norwood, MA, 1995.

This treatise is well written, and covers the topics that are essential elements of a successful processing approach for fully-focused radar altimetry. Spotlight SAR in most implementations uses stretch (credit, Bill Caputi), a range modulation method that in the radar altimetry literature is known as full range deramp (terminology due to John McArthur). That technique is ideally suited for managing wide-bandwidth returns arising from a scattering area of much smaller depth than the radar's range to that area, a trait that is common to altimeters and Spotlight SARs.

Soumekh, M., *Synthetic Aperture Radar Signal Processing with MATLAB Algorithms, 1st ed.,* Wiley-Interscience, 1999, 648 pages.

Some may find the MATLAB M-files useful. Mehrdad takes a somewhat different approach than other SAR processing books.

Kusk, A., J Dall, "ASAR SAR focusing of P-band ice sounding data using back-projection", *Proceedings IEEE International Geoscience and Remote Sensing Symp,* 2010. p. 4071-4074.

Back-projection is an alternative to the conventional approach to along-track (SAR) focusing. It works very well in certain circumstances, especially radar sounding and very wide (percent) bandwidth situations, but apparently it has not been applied previously to radar altimeter returns. Usually it is slower than the matched filter method, but it works better against a variety of signal modulations.

Wahl, D. E., P. H. Eichel, D. C. Ghiglia, P. A. Thompson, and C. V. Jakowatz, *Spotlight-Mode Synthetic Aperture Radar: A Signal Processing Approach*, Springer, 430 pages, 1996.

These folks from Sandia National Laboratories for decades have set the standard for airborne Spotlight SAR. Their approach favors the back-propagation algorithm. Although this book was published twenty years ago, it remains essentially the state-of-the-art.