Keynote

Milestones in altimeter performance: Past, Present, and Future

with relevance to Coastal Altimetry

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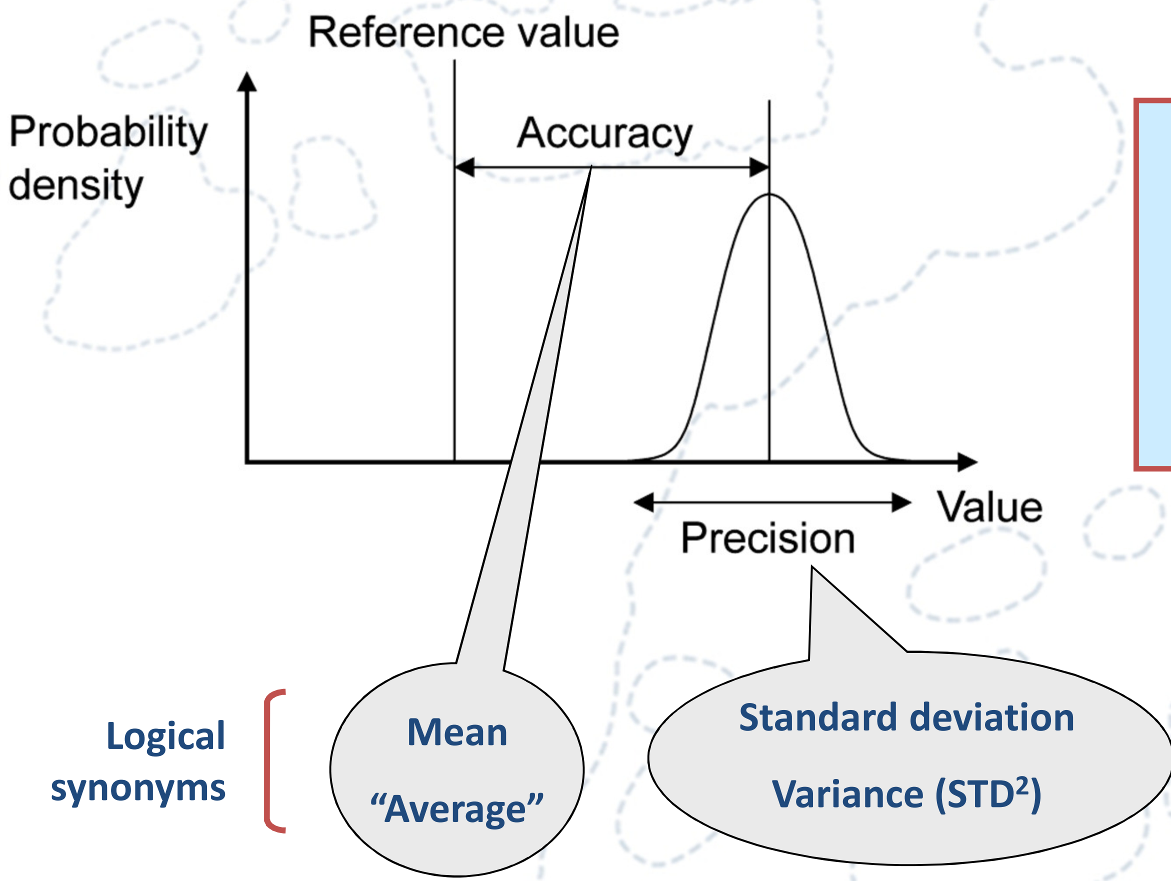
Outline

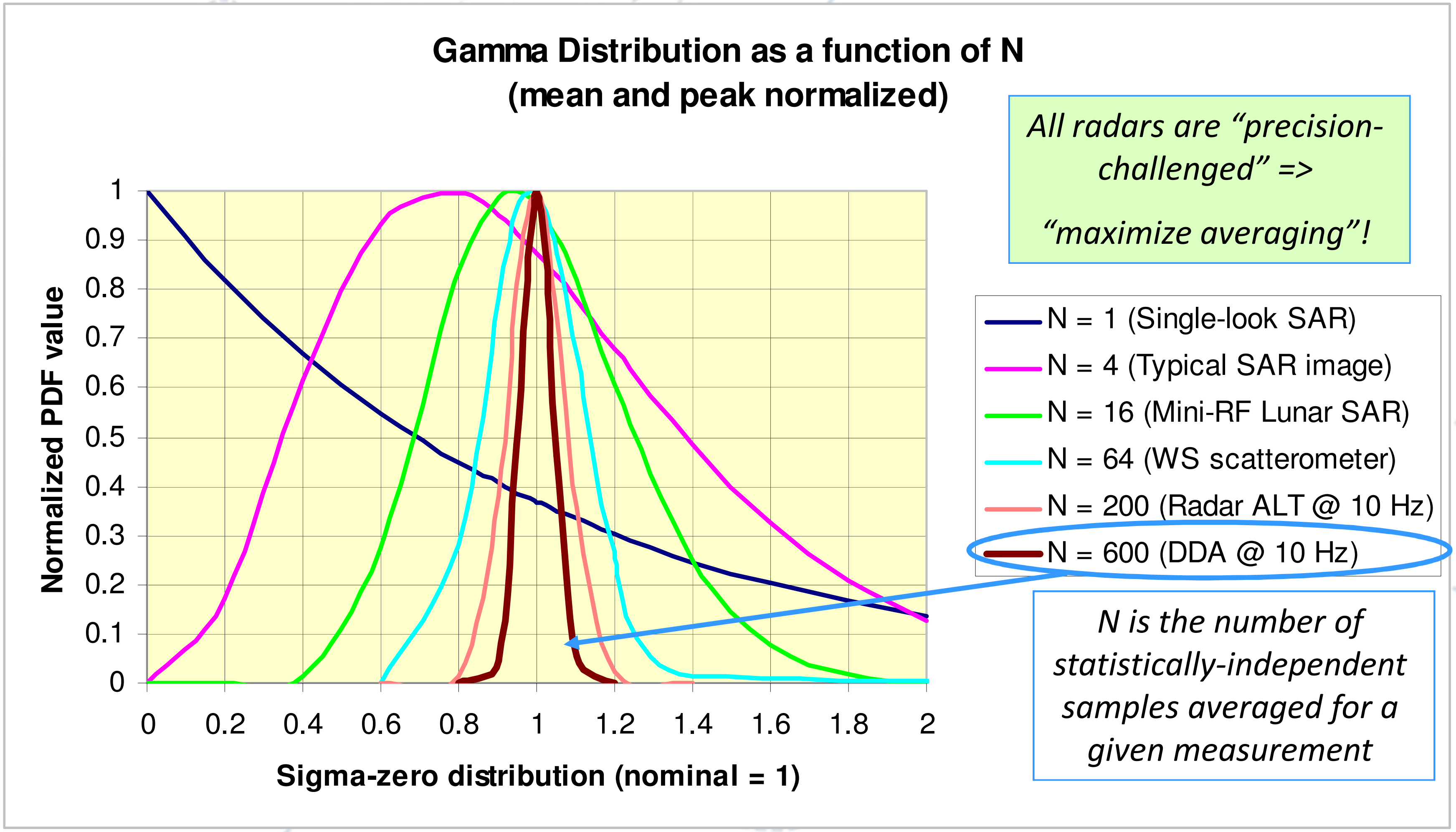
- Foundations
- The "conventional" altimeter
- Delay-Doppler
- Maximizing (SSH) precision
- Further possibilities
- Conclusions

Accuracy *vs* Precision



ACCURACY
and
PRECISION
two common terms;
emphasis here is on
Precision

On Precision (*wrt* Radar Self-Noise)



The "conventional" altimeter

1973: Skylab

Short pulse: proof of concept altimeter

1975: GEOS-3

LFM pulse; "Brown model", pulse-limited footprint

1978: Seasat

Full de-ramp (long linear fm pulse), ***also known as "stretch"***

1985 – "recently": ***Same basic approach: "LRM"***

Geosat; GFO

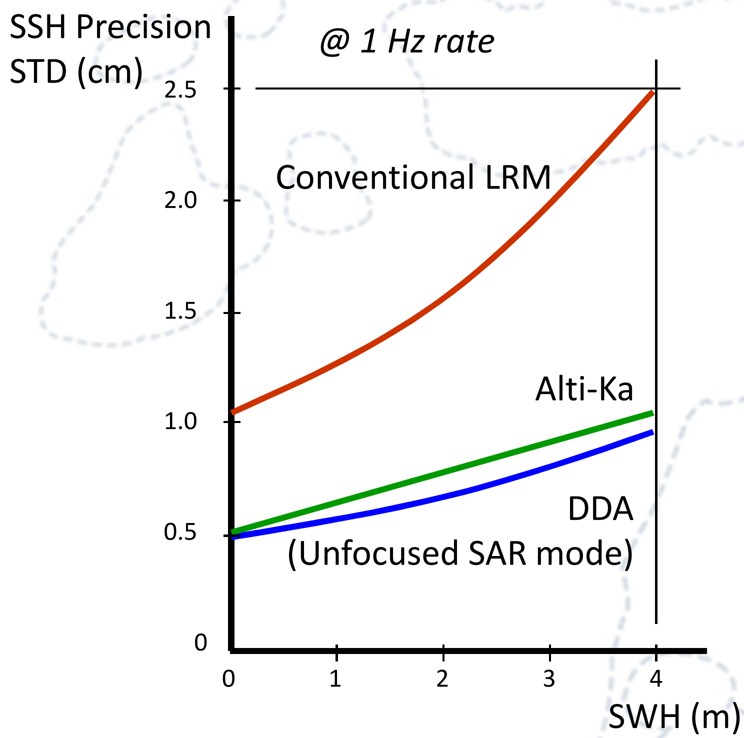
ERS-1, -2; Envisat

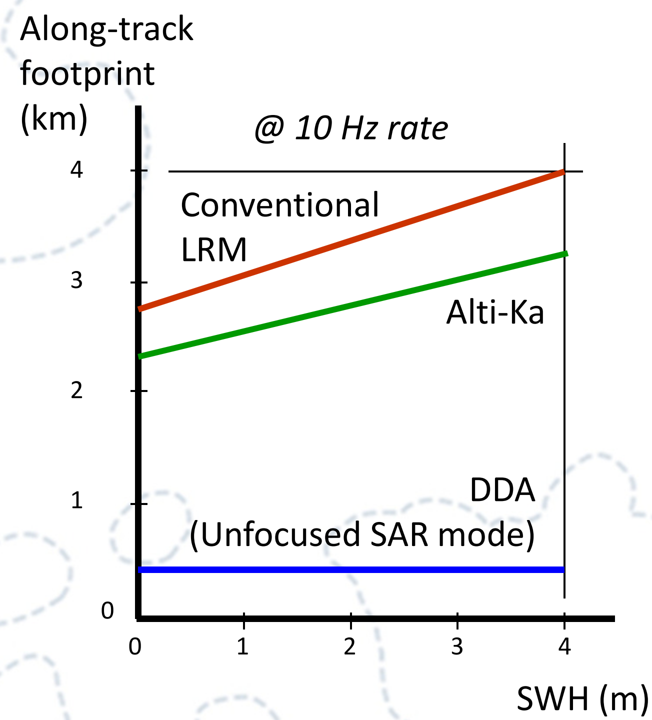
Topex/Poseidon; Jason-1, 2

Alti-Ka ***(LRM, but wider BW, shorter wavelength)***

Green underbars denote milestones

Precision and (*along-track*) Footprint





From simulations, courtesy CNES and JHU/APL

$$X_{LRM} \approx \left(1 + \frac{4}{7} SWH\right) D_{PL} + 7\, t_P$$

$$X_{Dop} \approx 7\, t_P$$

$$\text{where} \quad t_P = \frac{1}{\text{posting rate in Hz}}$$

Delay-Doppler Altimeter

2005: (CryoSat-1 => *"CryoSat paradigm" DDA*)

2010: CryoSat-2

Full de-ramp

Footprint: Doppler beam-limited (along-track)

Pulse-limited (across-track)

Closed burst

Multi-mode

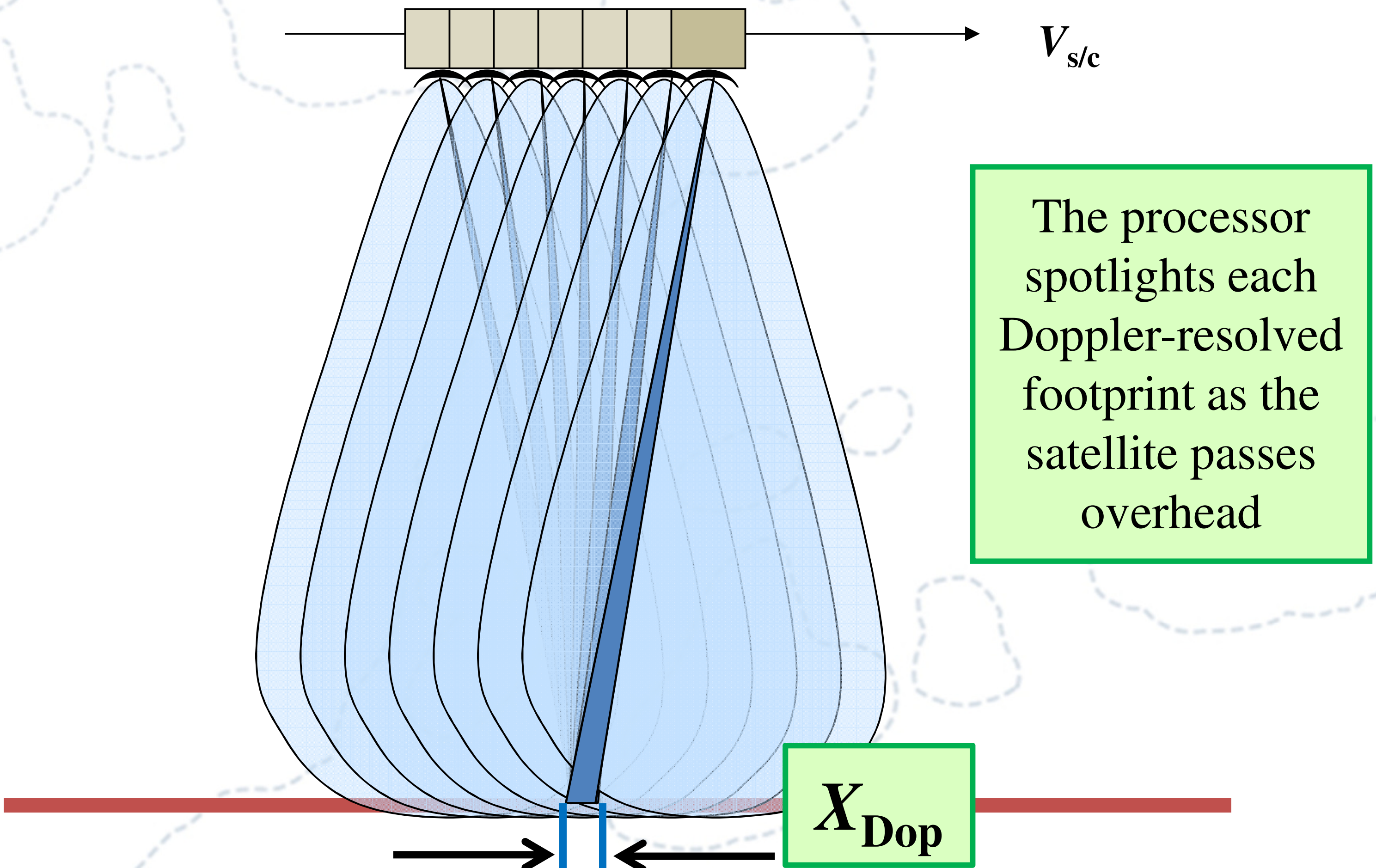
(201x): Sentinel-3

The CryoSat paradigm (*"SAR mode", no interferometer*)

or LRM

The Delay-Doppler Mode

(in effect, parallel along-track beam-limited altimeters !)

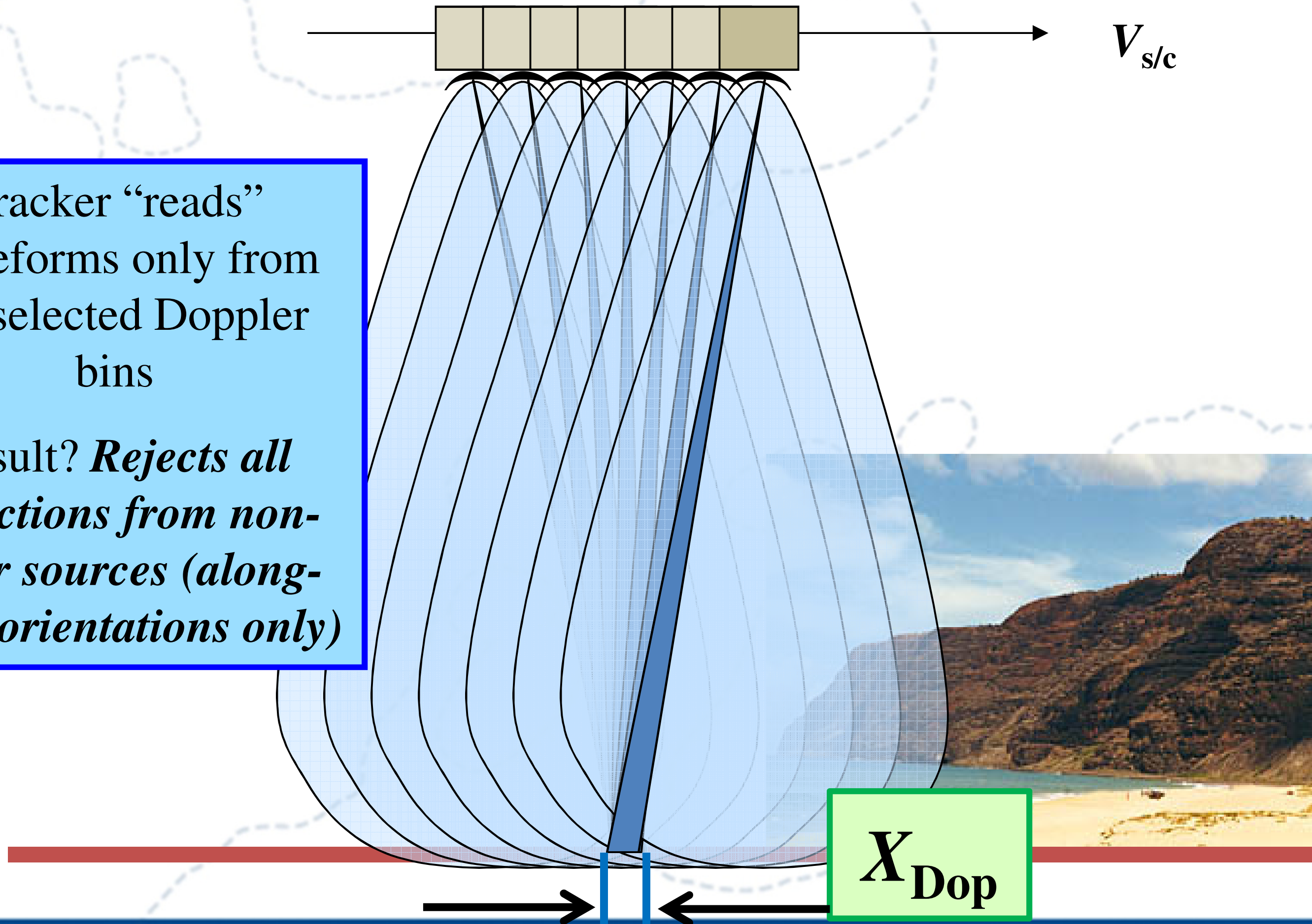


DDA – Coastal approach/retreat

(takes advantage of narrow beam-limited coverage)

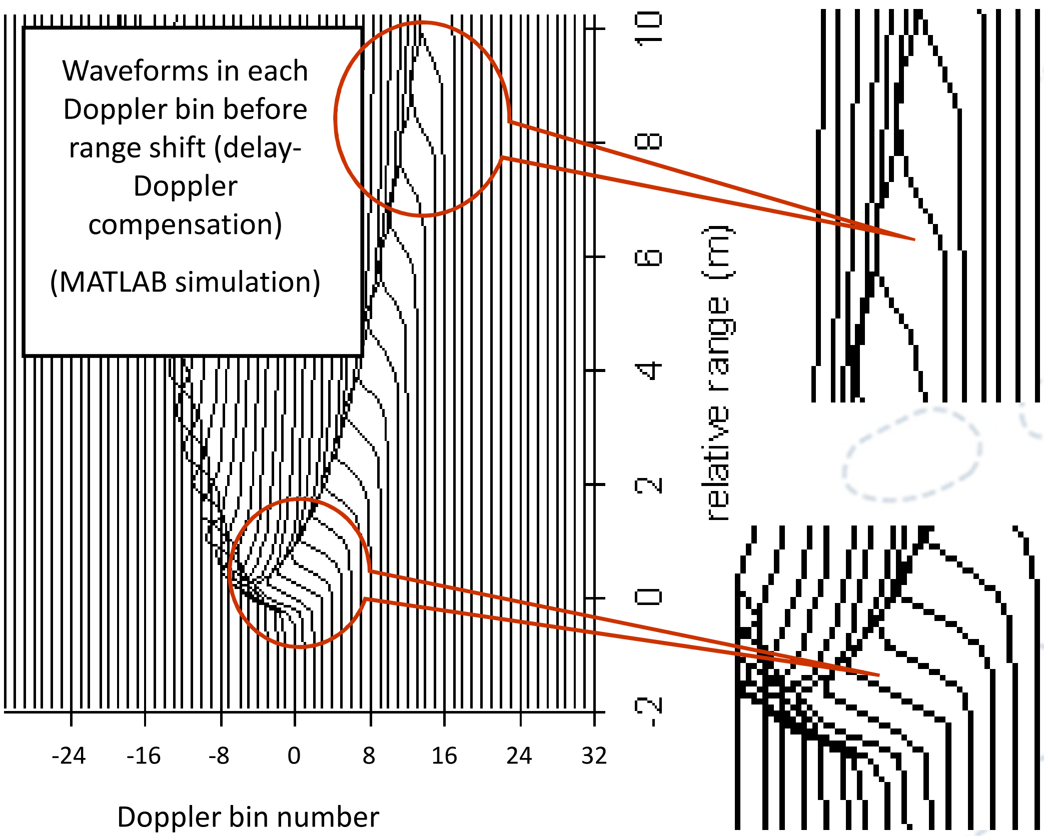
Tracker "reads" waveforms only from the selected Doppler bins

Result? ***Rejects all reflections from non-nadir sources (along-track orientations only)***



Useful Doppler bins

(diminishing returns for larger off-nadir angle)



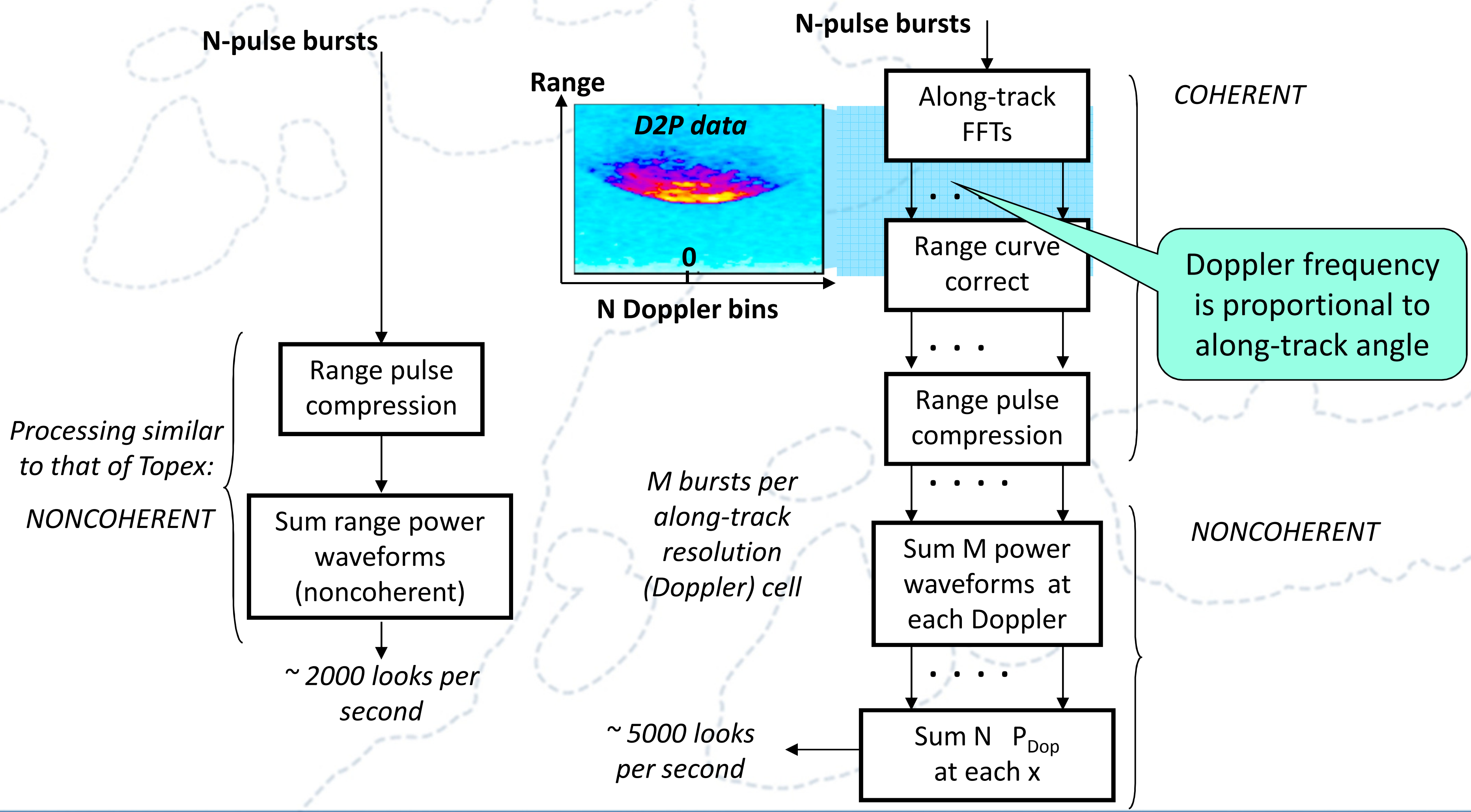
Raney, IGARSS95; Raney, TGARS 1998

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

$$N_{useful} \approx \frac{2\,h\,n\,\rho_{rng}}{X_{Dop}^{2}}$$

Moore and Williams, Proceedings IRE, vol 45, pp228-238, 1957.

DDA: *unfocused** SAR mode Altimetry

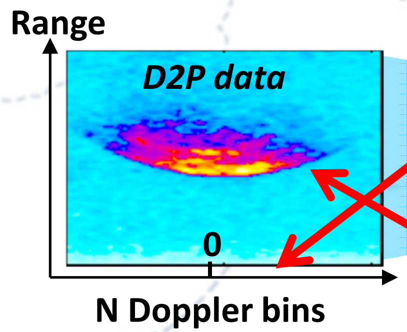


DDA: *unfocused** SAR mode Altimetry

Delay-Doppler was renamed "SAR Mode" BUT it actually is "unfocused SAR processing"

(True "SAR Mode" requires an azimuth matched filter)

N-pulse bursts



Along-track FFTs — DOPPLER

. . .

Range curve correct — DELAY

. . .

Range pulse compression

COHERENT

. . . .

Sum M power waveforms at each Doppler

. . . .

Sum N P_{Dop} at each x

NONCOHERENT

~ 5000 looks per second

Range pulse compression

Sum range power waveforms (noncoherent)

~ 2000 looks per second

Processing similar to that of Topex:

*Cutrona and Hall, 1962

Interleaved Mode

(20yy): Jason-CS / Sentinel - 6

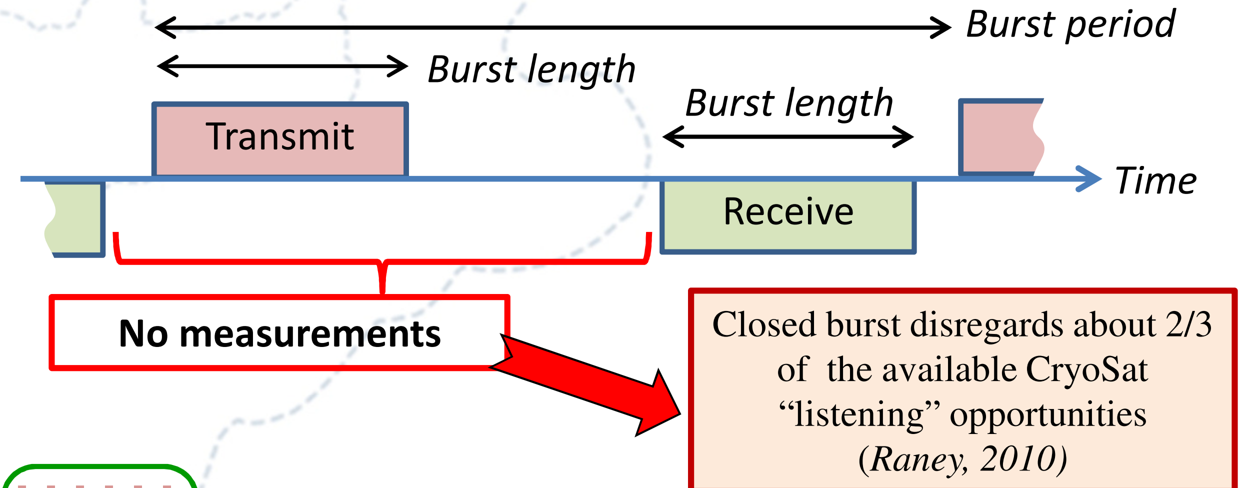
Open burst => interleaved Tx and Rx pulses

Simultaneous unfocused SAR mode *and* LRM (*via decimation*)

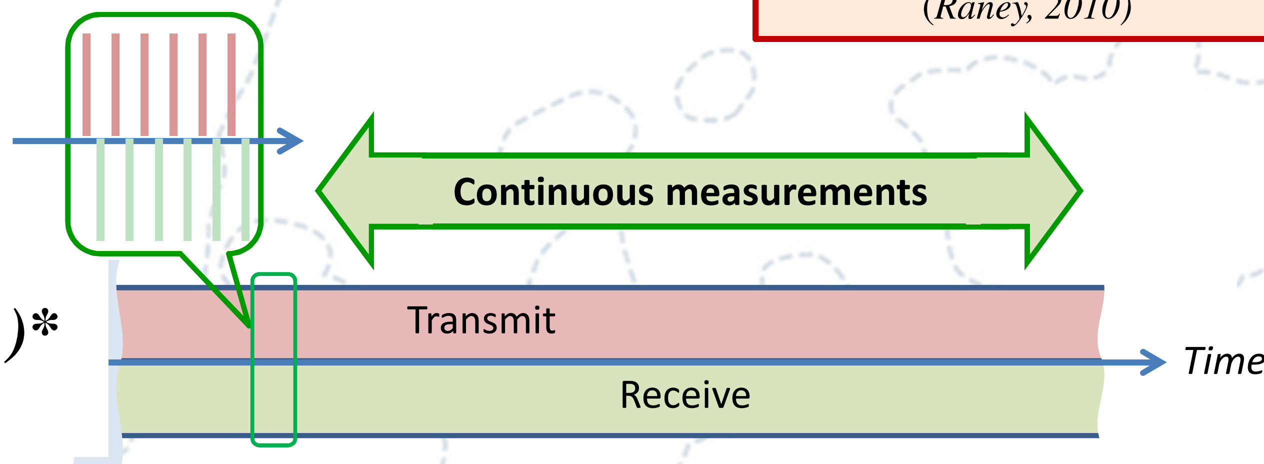
Assures continuity with 22+ years of accumulated data

Closed Burst *vs* Open Burst

Closed burst method



Interleaved / Open burst *(conventional !) method**



*Precedent: TOPEX (*Zieger et al, 1991*)

Maximum # of uncorrelated looks

(unfocused SAR mode , interleaved)

$$N_{sec} = N_{bin}\, N_{dt}\, N_{useful}$$

Number of looks per second (~10,000)

Maximum number of statistically independent looks within each Doppler bin

$$N_{bin} = \frac{2\alpha X_{Dop}^{2}}{h\lambda}$$

evaluated for the maximum burst repetition frequency (generalized Walsh bound)

Number of Doppler bins (at nadir) traversed per second

$$N_{dt} = \frac{V_{sc}}{\alpha X_{Dop}}$$

$$\alpha = \frac{V_{SC}}{V_{foot}}$$

A Fundamental Limit

(unfocused interleaved SAR mode)

- **Open burst (=> interleaved mode)** ***vs*** **Closed burst**

  Interleaved mode, ideally with a quasi-continuous pulse-repetition frequency PRF,

  - ✓ ***maximizes the available "listening time",***
  - ✓ ***thus maximizing the number of available looks,***
  - ✓ ***thus maximizing averaging,***

- ***thus*** **minimizing the SSH measurement uncertainty (~ 5 mm @ Ku)**

$$< \Delta r > = \left(\frac{\lambda \, \rho_{rng} \, X_{Dop}}{4 \, n \, V_{sc}} \right)^{1/2}$$

1st implementation : Jason-CS / Sentinel-6

Further possibilities (1 of 2)

of particular relevance to coastal altimetry

- **Orbit selection**

A non-repeat orbit (e.g. 1st 18 months of Geosat) would benefit geodesy, meet oceanographic requirements, and should be of interest for coastal applications

- **Reduced cross-track footprint / selectivity**

Two degrees of freedom in instrument design have yet to be investigated:

***polarimetry** (e.g., transmit CP, receive two orthogonal polarizations);*

***coherence** * (e.g., look for "persistent scatterers" in the sequence of backscattered signals, hence suppressing most land returns)*

* Could be investigated using full waveform data

Further possibilities (2 of 2)

of particular relevance to coastal altimetry

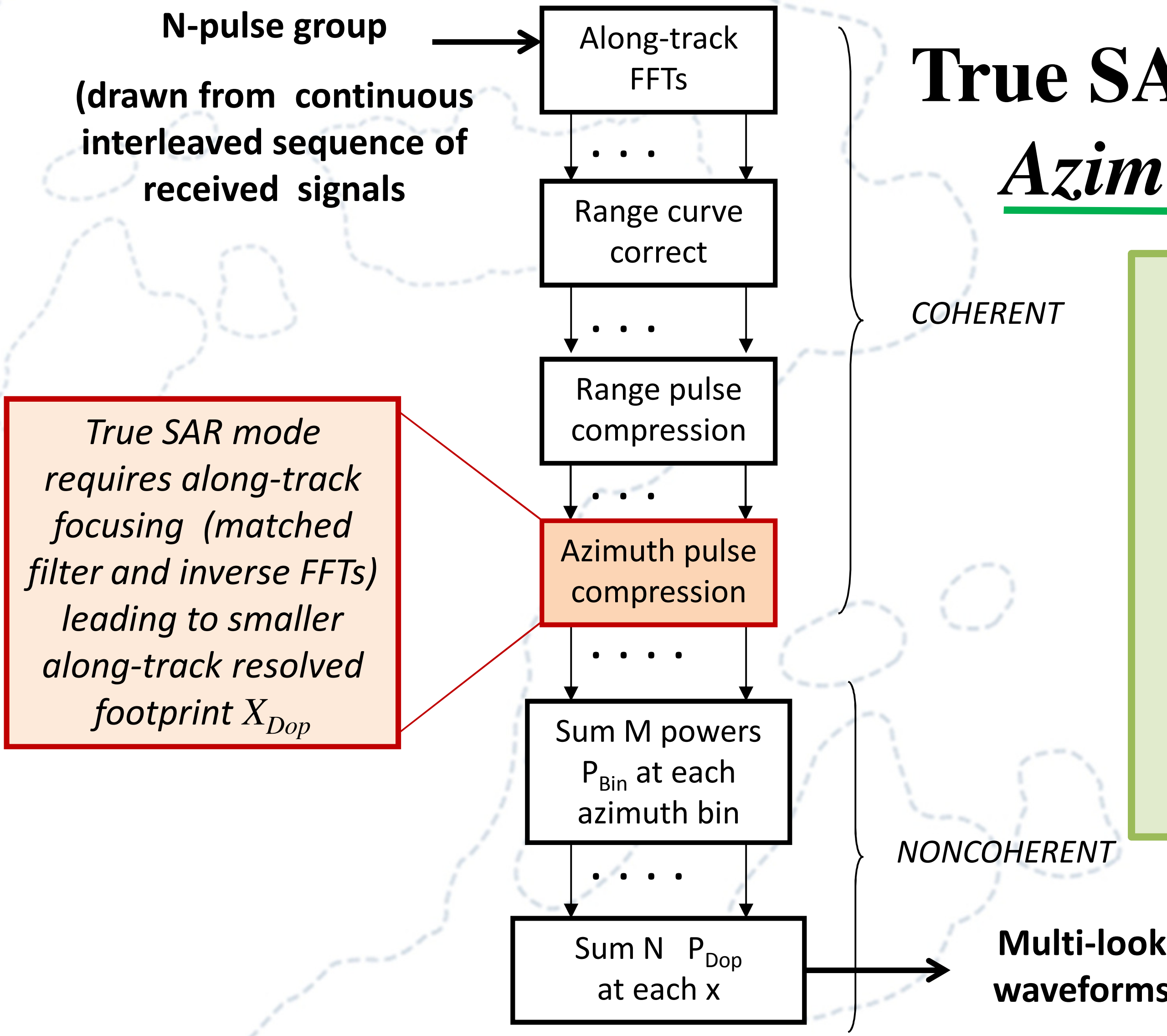
- **Multi/wide swath altimetry**

  Such an instrument possibly will fly in future, but the achievable precision (averaging!) and effectiveness in near-shore environments have yet to be demonstrated

  NB: The CryoSat-2 SARIn Mode could be exercised to explore this approach. For example, roll the s/c ~1.5 degrees to make it a ***nadir altimeter & side-looking imaging SAR interferometer*****; gather data over the ocean as well as over ocean/land scenes; estimate SSH of nadir & generate a near-nadir imaging swath**

- **Delay-Doppler** ***vs*** **(true) SAR mode**

True SAR-mode => *Azimuth focus*



What is the finest possible along-track resolution?

How many looks?

Precision *vs* Resolution

Number of looks x (1 / Resolution) < Constant

A radar measurement **Uncertainty Principle**

From information theory: resolution and statistically independent looks both require bandwidth (channel capacity)

If all data are collected and processed through a true SAR mode focusing algorithm, the smallest along-track footprint is

$$D / 2\alpha = \rho_{at} \approx 0.5\ m$$

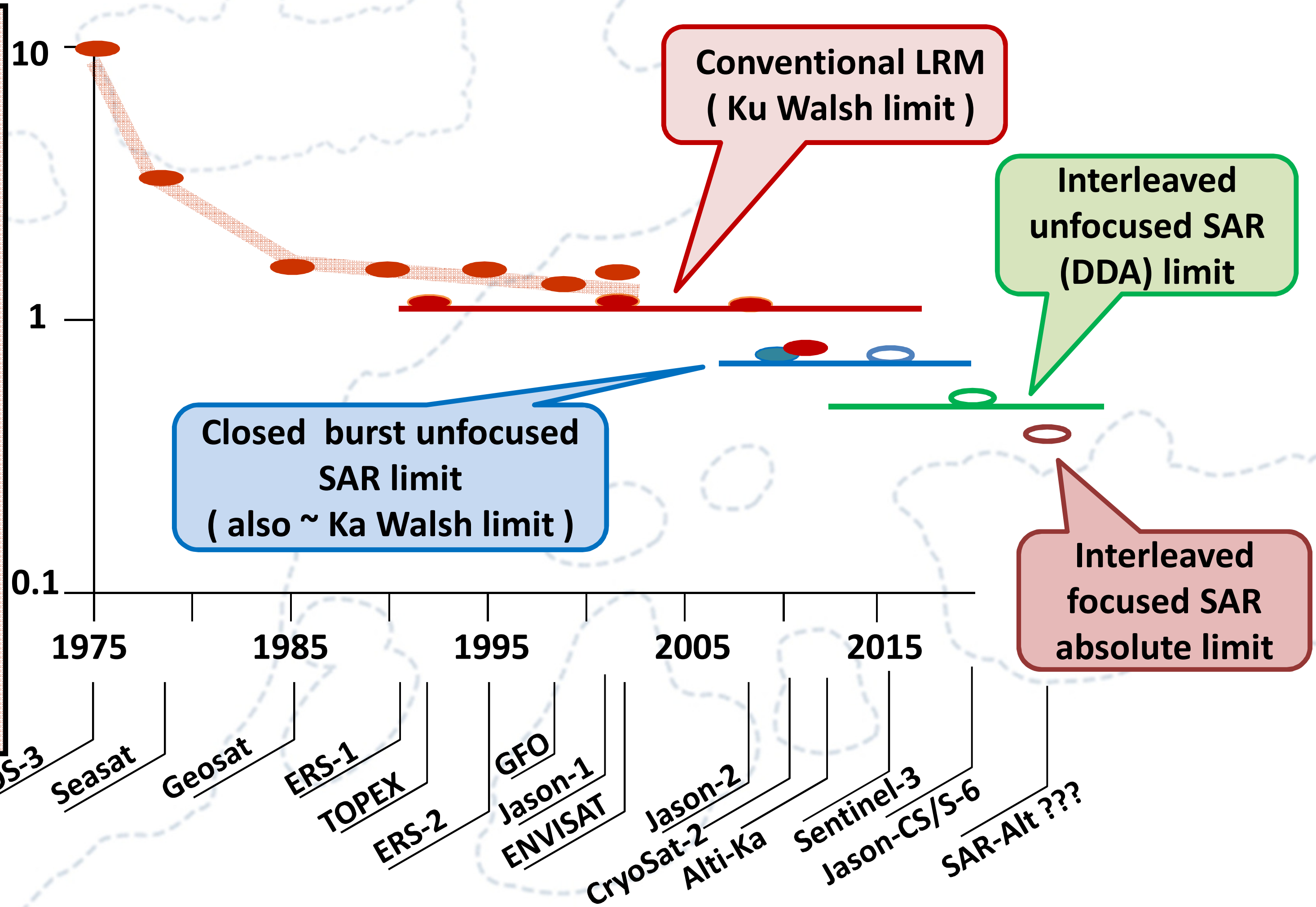
@ one look, which leads to the maximum number of looks per second

$$N_{SAR_{max}} = V_{foot} / \rho_{at} \approx 14{,}000$$

Why? *Small* $X_{Dop} \rightarrow \rho_{at}$ *implies that all Doppler bins are "useful"*

SSH (1-Hz) Precision Trends (cm)

Height ***PRECISION*** *(instrument dependent) is the essential measurement attribute for geodesy, bathymetry, and mesoscale oceanography, and enhances near-shore measurements*



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  Especially for coastal applications: "beam-limited"

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  Especially for coastal applications: "beam-limited"
- **Focused SAR:** ***smaller along-track resolution, more looks/sec***

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- **Focused SAR:** ***smaller along-track resolution, more looks/sec***
- **Major milestone:** ***Interleaved simultaneous DDA and LRM***

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- **Finer SSH instrument precision is critical for coastal apps**
  Finer instrument precision => less averaging time needed
- **Unfocused SAR mode (DDA): significant milestone**
  Especially for coastal applications: "beam-limited"
- **Focused SAR:** ***smaller along-track resolution, more looks/sec***
- **Major milestone:** ***Interleaved simultaneous DDA and LRM***
- **Twenty-five-year future milestone?**

  SAR-Alt: Focused nadir polarimetric SAR altimeter & side-looking SAR interferometer & LRM in non-repeating orbit