CryoSat Data as Delay-Doppler Proof of Concept

R. K. Raney

Johns Hopkins University Applied Physics Laboratory

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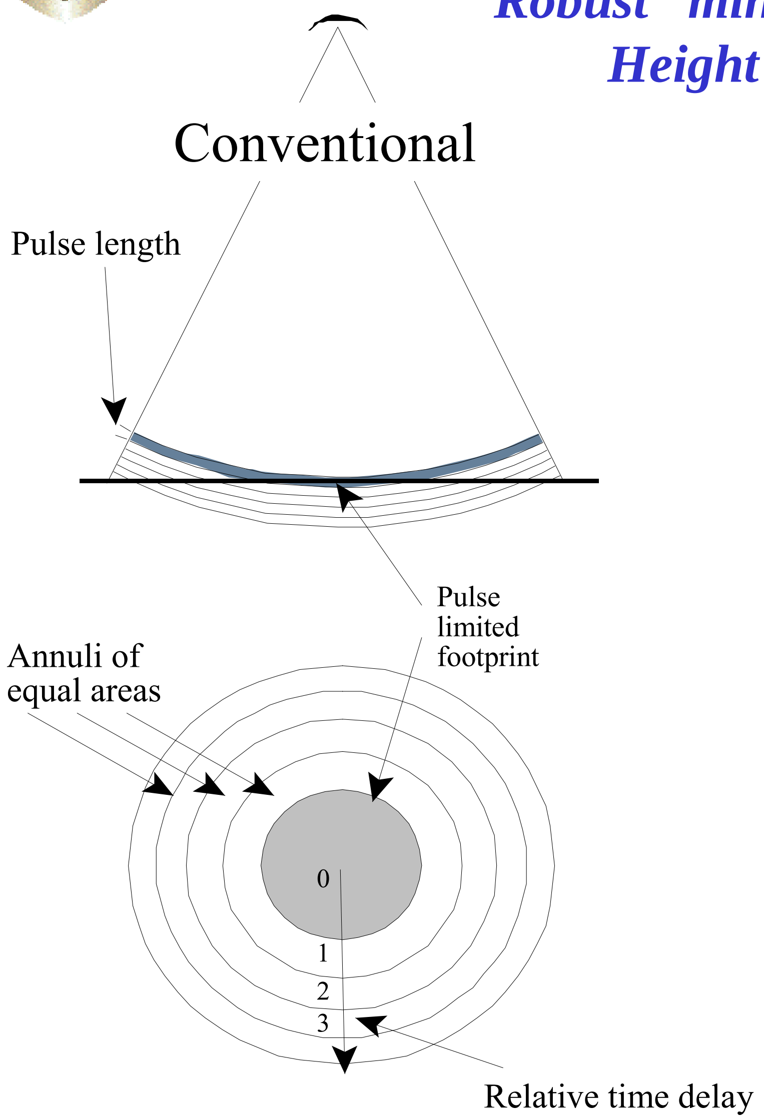
The Main Points

CryoSat SARM Data over water

- Conventional radar altimeter (RA) *versus* Delay-Doppler (DDA)
- Airborne (CryoSat) prototype: the D2P altimeter
- Delay-Doppler processing
- The CryoSat SAR mode (SARM ~ DDA)
- Hypothesis: $\boldsymbol{\textit{Precision of SSH}_{DDA}}$ < $\boldsymbol{\textit{precision of SSH}_{RA}}$
- Experiment: Proof-of-concept using SARM ocean data
- Conclusions

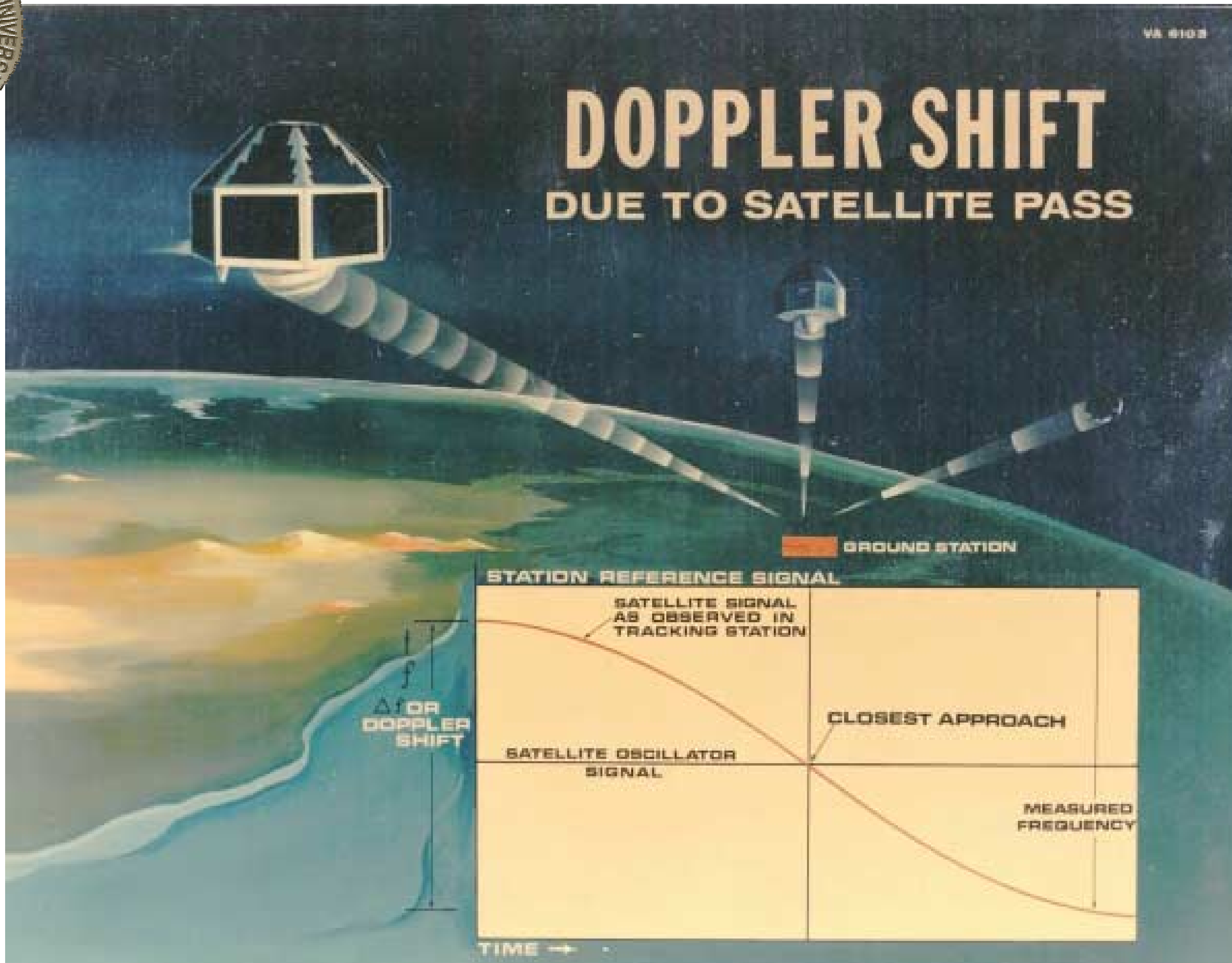
Pulse-Limited Radar Altimetry

Robust "minimum-range" Sea Surface Height (SSH) measurements



- SSH accuracy (to first order) does NOT depend on attitude control/knowledge of the s/c (+)
- Instantaneous pulse-limited footprint diameter D_{SWH} grows larger with increasing SWH (X)
- Sample posting rate @ N Hz gives rise to an effective footprint along-track length $L_{eff} \approx (D_{SWH} + 6.7/N)$ km (X)

Original APL *Transit* concept



Delay-Doppler Paradigm*

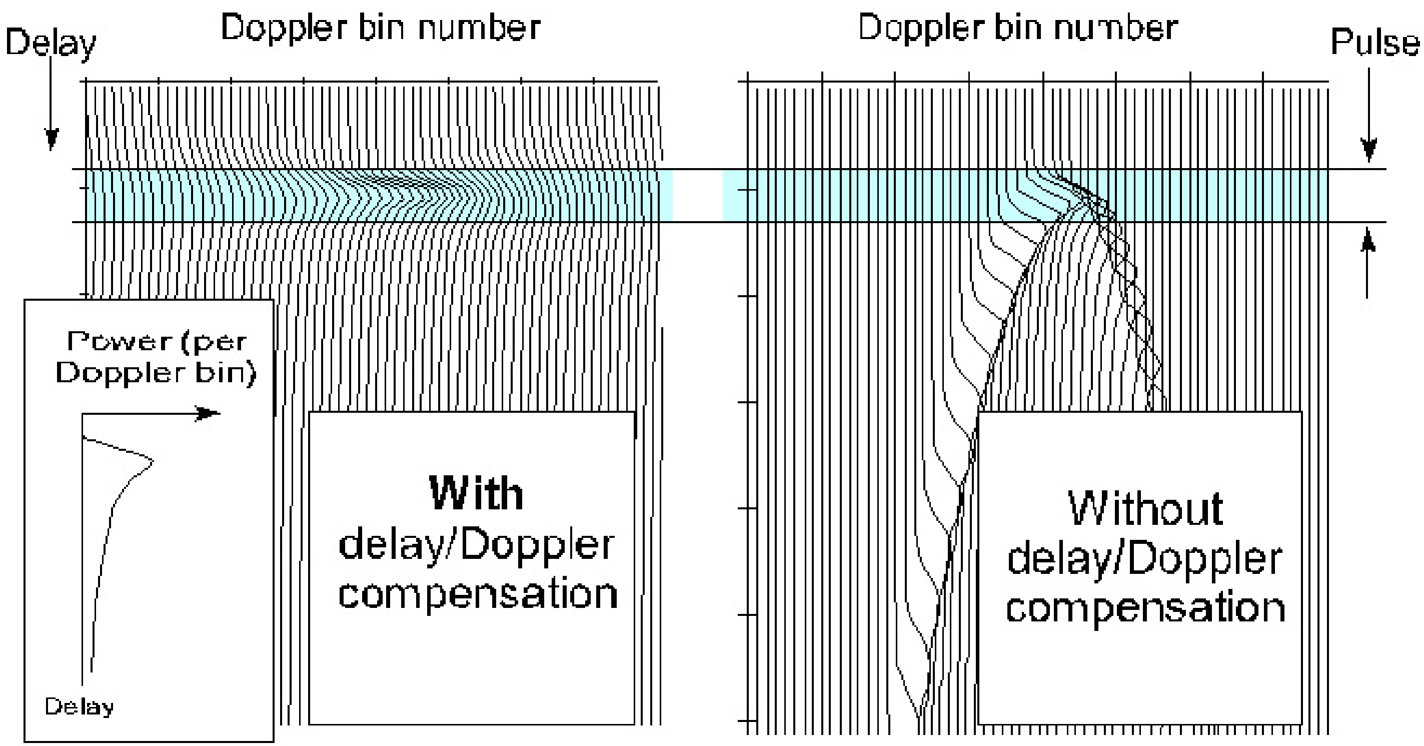
. . . exploits synthetic aperture radar (SAR) techniques

Unfocused along-track processing: FFTs

Range curvature removal

Range pulse-compression: conventional IFFT

Incoherent (multi-look) summations at all Doppler bins



** Johns Hopkins University Applied Physics Laboratory, 1994*

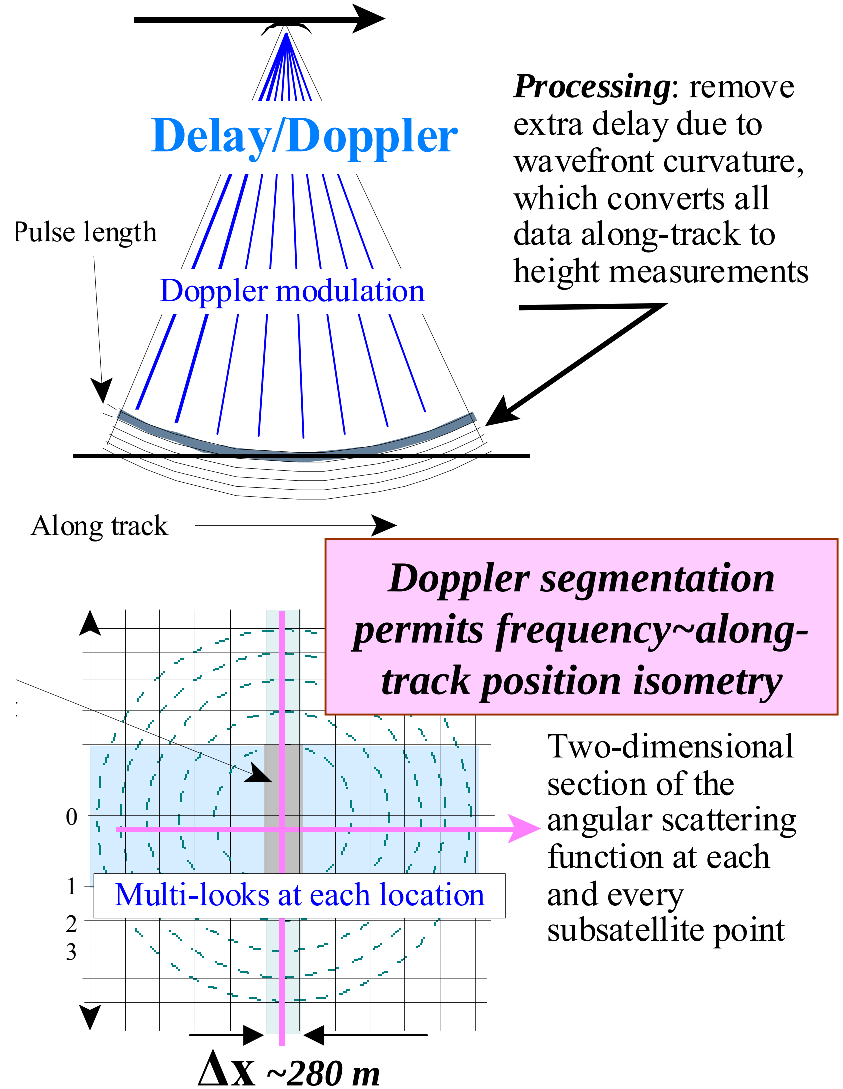
Delay-Doppler Encounter Geometry

Essentially the CryoSat SAR mode (SARM)

- DD paradigm retains advantages of a pulse-limited altimeter (+)
- SSH accuracy (to first order) does NOT depend on attitude control/knowledge of the s/c (+)
- Instantaneous pulse-limited footprint along-track length Δx is constant with increasing SWH (+)
- Sample posting rate @ N Hz gives rise to a constant effective footprint along-track length (+)

$$L_{eff} \approx (6.7/N)\ \text{km}$$

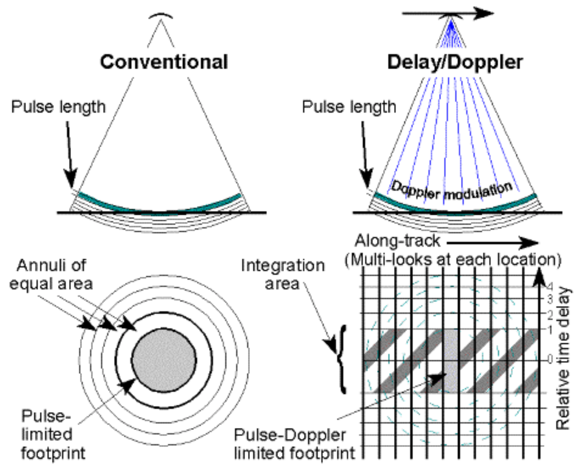
(lower bound ~ Δx @ ~30 Hz)



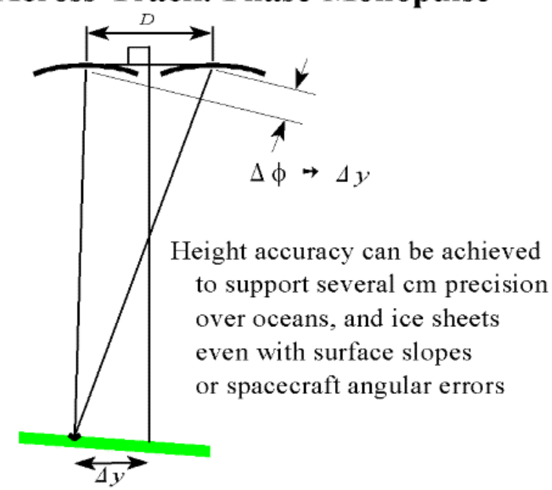
D2P: Airborne Delay-Doppler Altimeter

CryoSat Airborne prototype

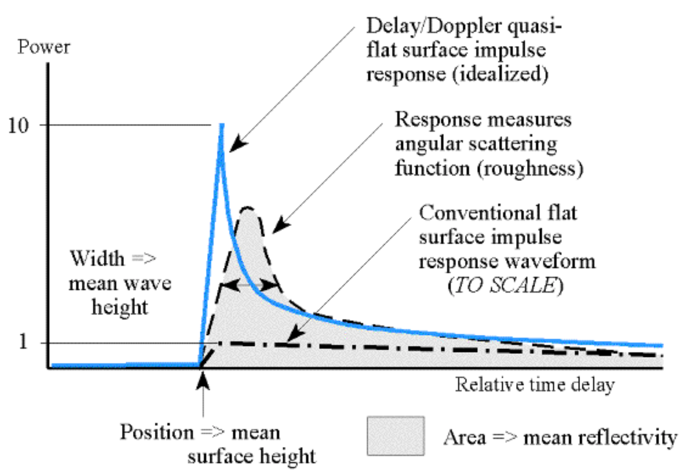
Along-Track: Doppler Processing

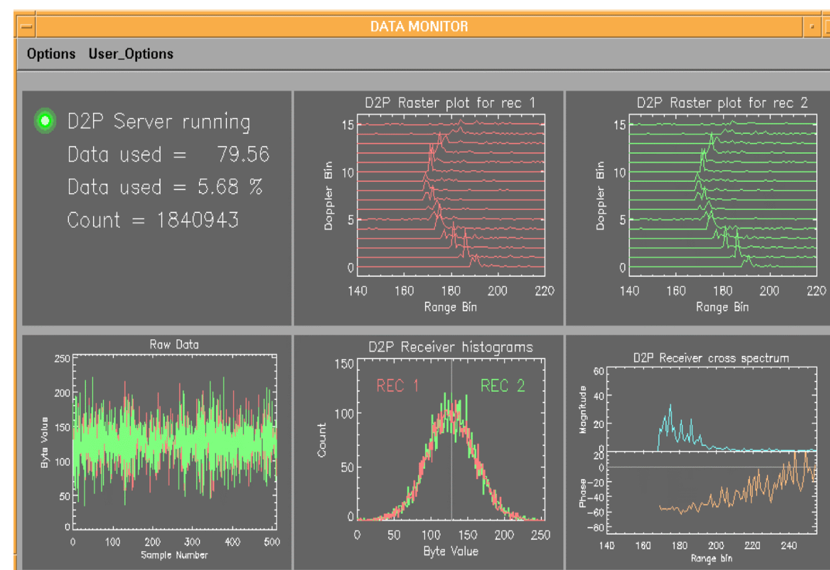


Across-Track: Phase-Monopulse



Altimeter response waveforms





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D2P* History

- November 1994 – delay-Doppler basic theory (APL) => D2P concept
- December 1998 – D2P prototype instrument design and build*
- December 1999 – first laboratory operation*
- June 2000 – Demonstration flights ***(NRL P-3)****
  - over southern Greenland and Davis Strait
- May 2002 – LaRA 2002**
- April 2003 – CryoVEx***
- Antarctica – 2003, 04*

**Acknowledge NASA*

*** Acknowledge ESA & NASA*

**** Acknowledge ESA, NASA, & Denmark*

NRL P-3

Proofs of Concept

Satellite-based demonstrations are required

Proven through aircraft flight tests

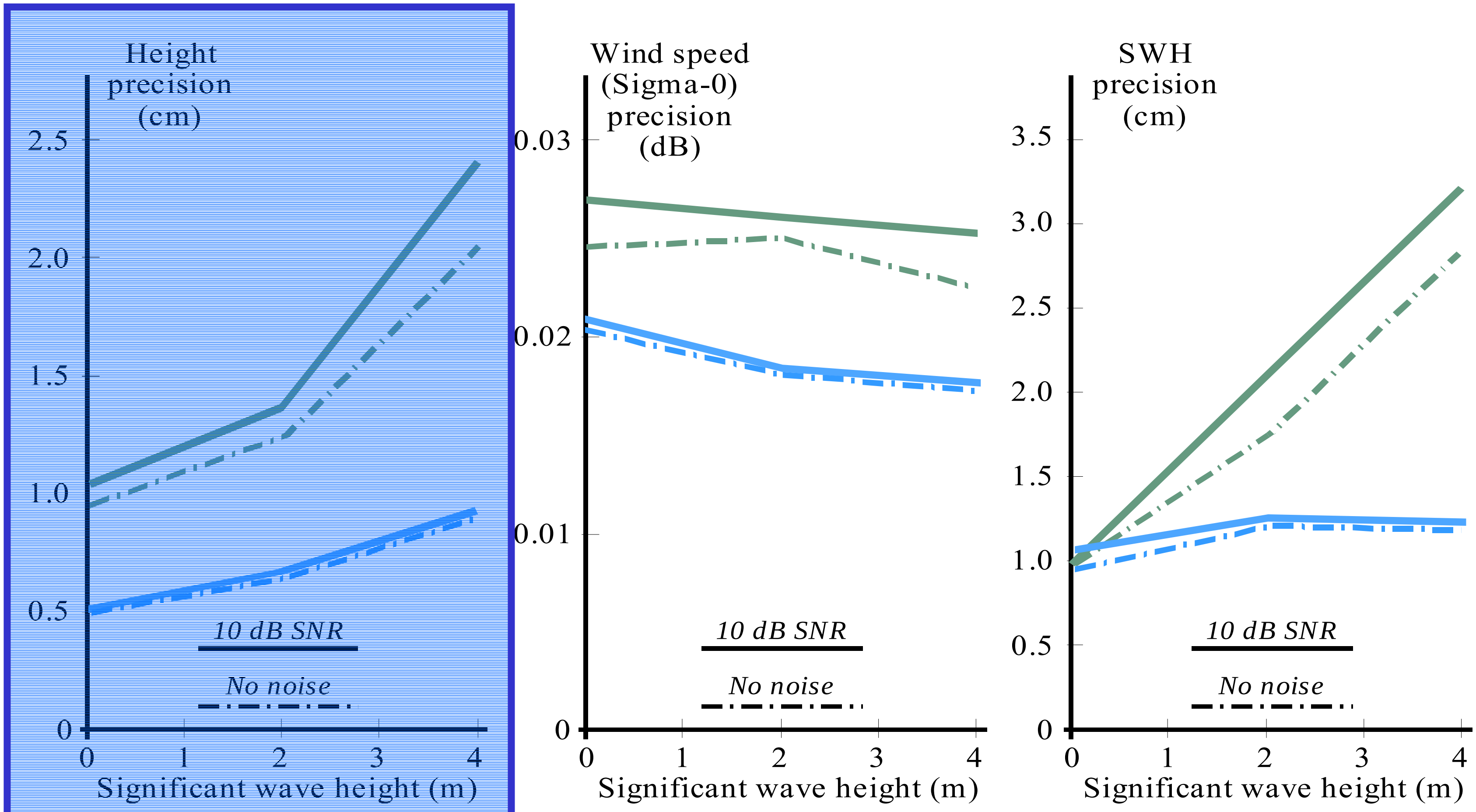
- Along-track Doppler processing
- Across-track interferometry
- Surface slope tolerance/measurement

Satellite data required for proof-of-concept

- Range-dependent performance (*resolution*, *etc*.)
- Velocity-dependent performance
- **RA vs DDA measurement precision**

Delay-Doppler Altimeter (DDA) vs Conventional:
Precision at 1 Hz Rate*

Delay/Doppler ~ x2 ***better*** *than conventional*

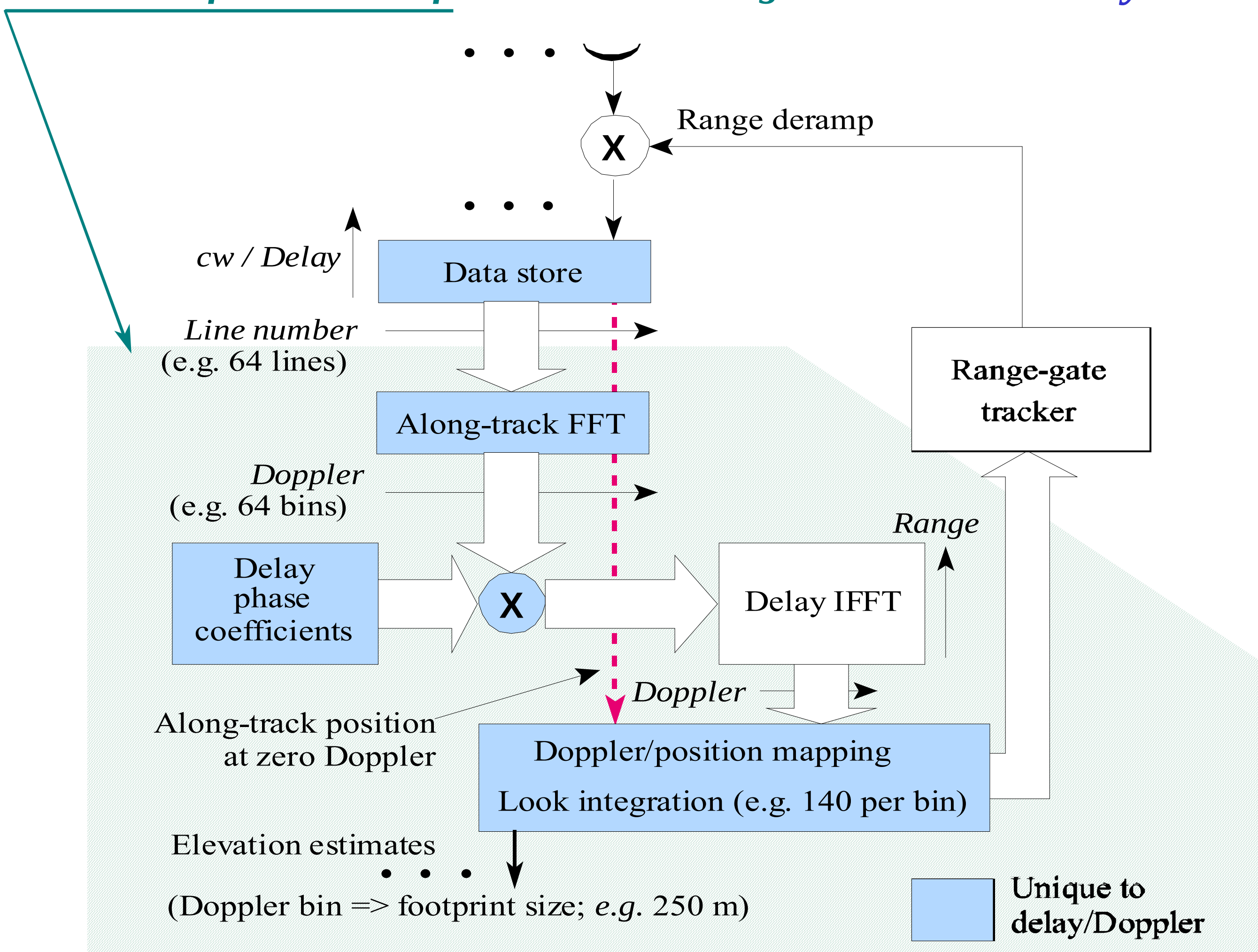


Courtesy: J. R. Jensen

* *Based on computer simulations*

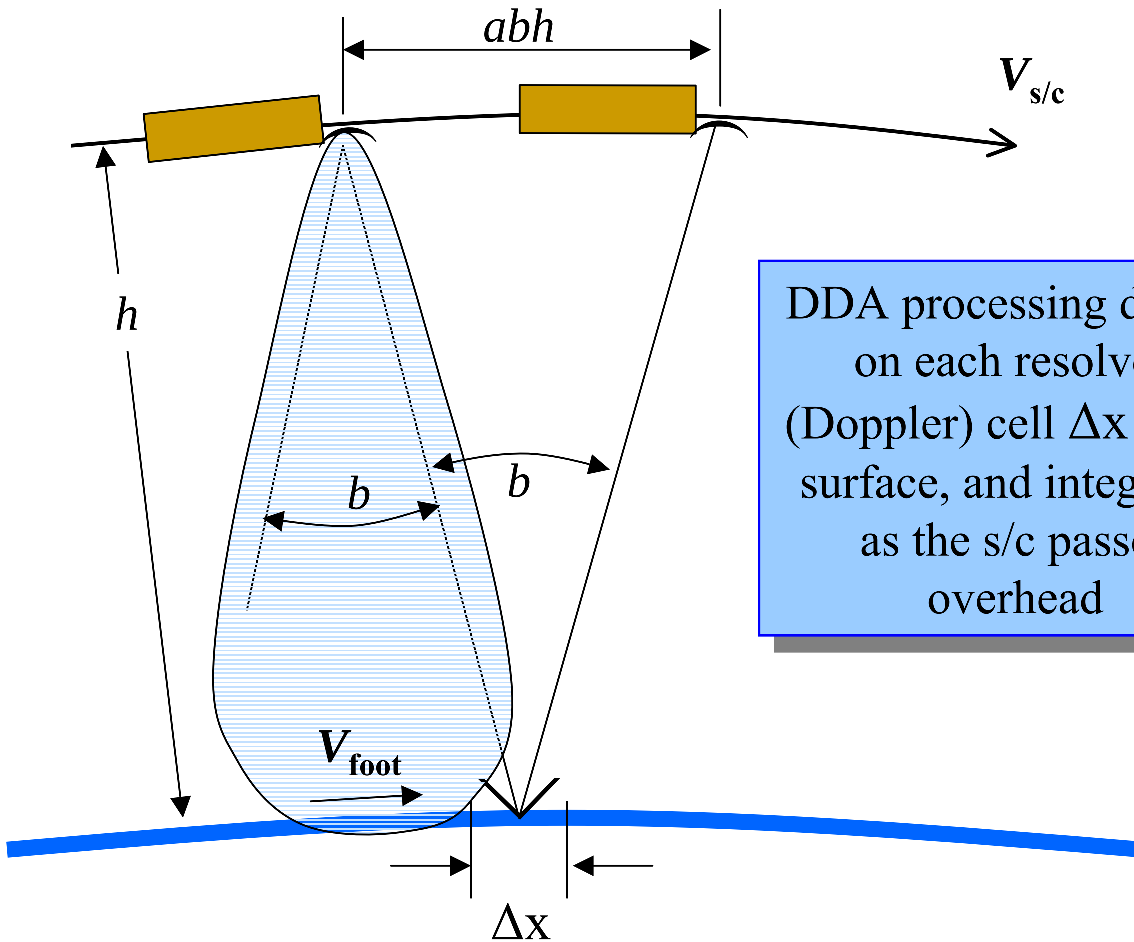
Delay Doppler Processing . . .

. . .for the aircraft demonstration is ground-based ***~ CryoSat***



Incoherent integration at each resolved footprint

The key to increased resolution and precision



$$a = \frac{R_E + h}{R_E}$$

DDA processing dwells on each resolved (Doppler) cell Δx at the surface, and integrates as the s/c passes overhead

SARM on CryoSat

Parameter summary

(Closed) burst operation

17.8 kHz prf, 64 pulses per burst

antenna diameter => T_{coh} ~ 8.3 μsec > 6 μsec = 1/prf

=> coherent within each burst

along-track (Doppler) cell size ~ 285 m > $SAR_{unfocused}$

85.5 Hz Burst rate (burst period 11.7 ms)

=> 5472 pulses per second (average)

=> ~ 80 m per burst (along surface track)

=> ~ 230 looks per (Doppler) cell

Processing: Incoherent vs Delay-Doppler

DDA: near-optimum partially coherent processing

SARM N-pulse bursts

Reduce instantaneous prf to suppress p-p coherence at no loss in SNR

Along-track pre-sum (n)

Range pulse compression

Sum range waveforms (incoherent)

Processing similar to that of Topex:

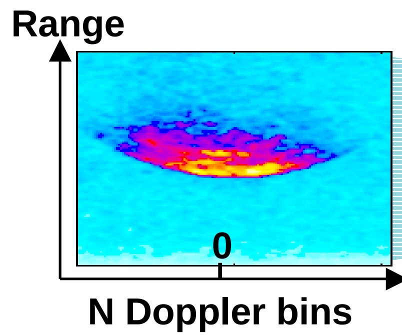
INCOHERENT

< 2500 looks per second

SARM N-pulse bursts

Along-track FFTs

COHERENT



Range/Doppler distribution unique to the DDA method

Range curve correct

Range pulse compression

M bursts per along-track resolution (Doppler) cell

Sum M powers P_{Dop} at each Doppler

INCOHERENT

Sum N P_{Dop} at each x

> 5000 looks per second

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The Experiment

CryoSat Data Opportunity

- Collect SARM data over the ocean
- Specific location is not constrained – *adapt to mission plan*
- RA process: Level-1 data => SSH_{RA}
- DDA process: ***using the same*** Level-1 data => SSH_{DDA}
- Compare SSH precisions (*variance, or standard deviations*)
- Repeat for a variety of significant wave heights

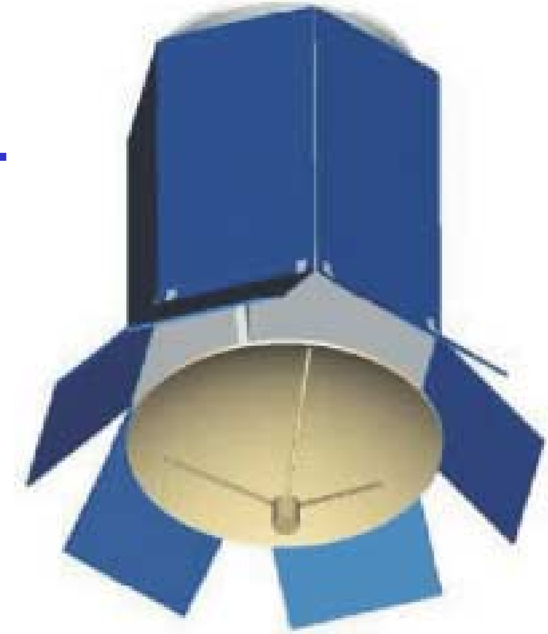
Conclusions

CryoSat SARM Data over water

- CryoSat will be the first coherent s/c altimeter
  SARM data will support either DDA or RA processing
- Ideal opportunity to compare DDA *vs* RA performance
  Quantitative; self-normalizing; robust
- Compare precisions of DDA *vs* RA SSH measurements
  To Prove: DDA SSH variance less than RA SSH variance
- Repeat comparisons for various SWH
  To Prove: lower SWH noise in DDA SSH measurements
- Expected result: DDA always better than a conventional RA
  Default processing mode emulates incoherent integration
- Cost-effective "litmus test" to compare inherent DDA *vs* RA advantages for oceanic applications ***(one way or another :-)***

RESOURCE SLIDES

The Baseline Abyss-Lite Design**

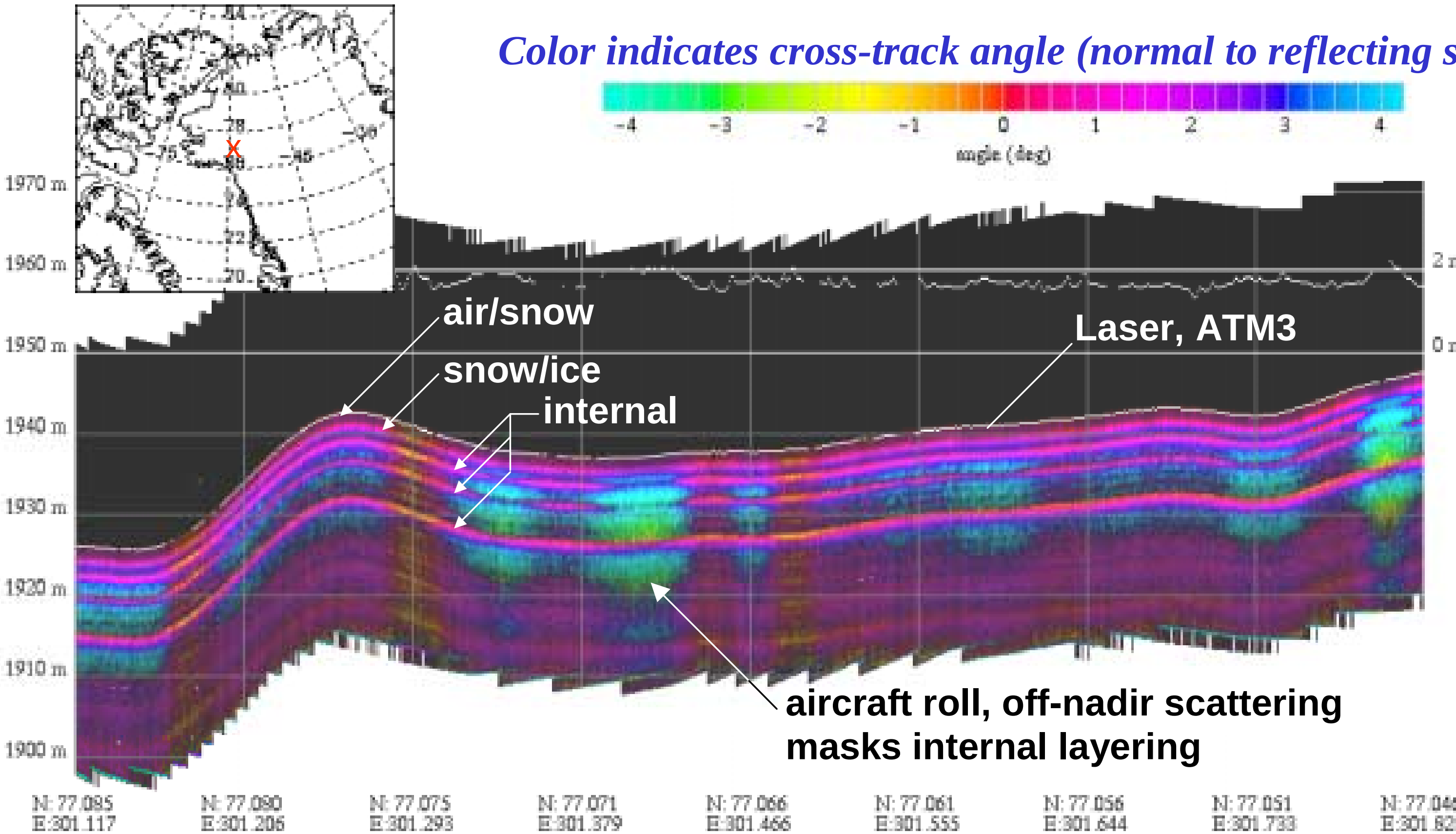


Radar mass (kg)	~ 28
Spacecraft mass (kg)	148
Antenna diameter (m)	1.0
Science data rate (kb/s)	25 (average)
Radar power (W)	< 75 (fixed solar arrays)
D/L data rate (Mb/s)	4 (two days of data, 10 min)
Navigation	Star-trackers & GPS
Attitude control	Pitch wheel and torque rods
Launch	Pegasus (60 degrees#)

****Design study at JHU/APL funded by NOAA*

****Excluding reserves and launch vehicle*** ***#Additional cost of retrograde orbit TBD***

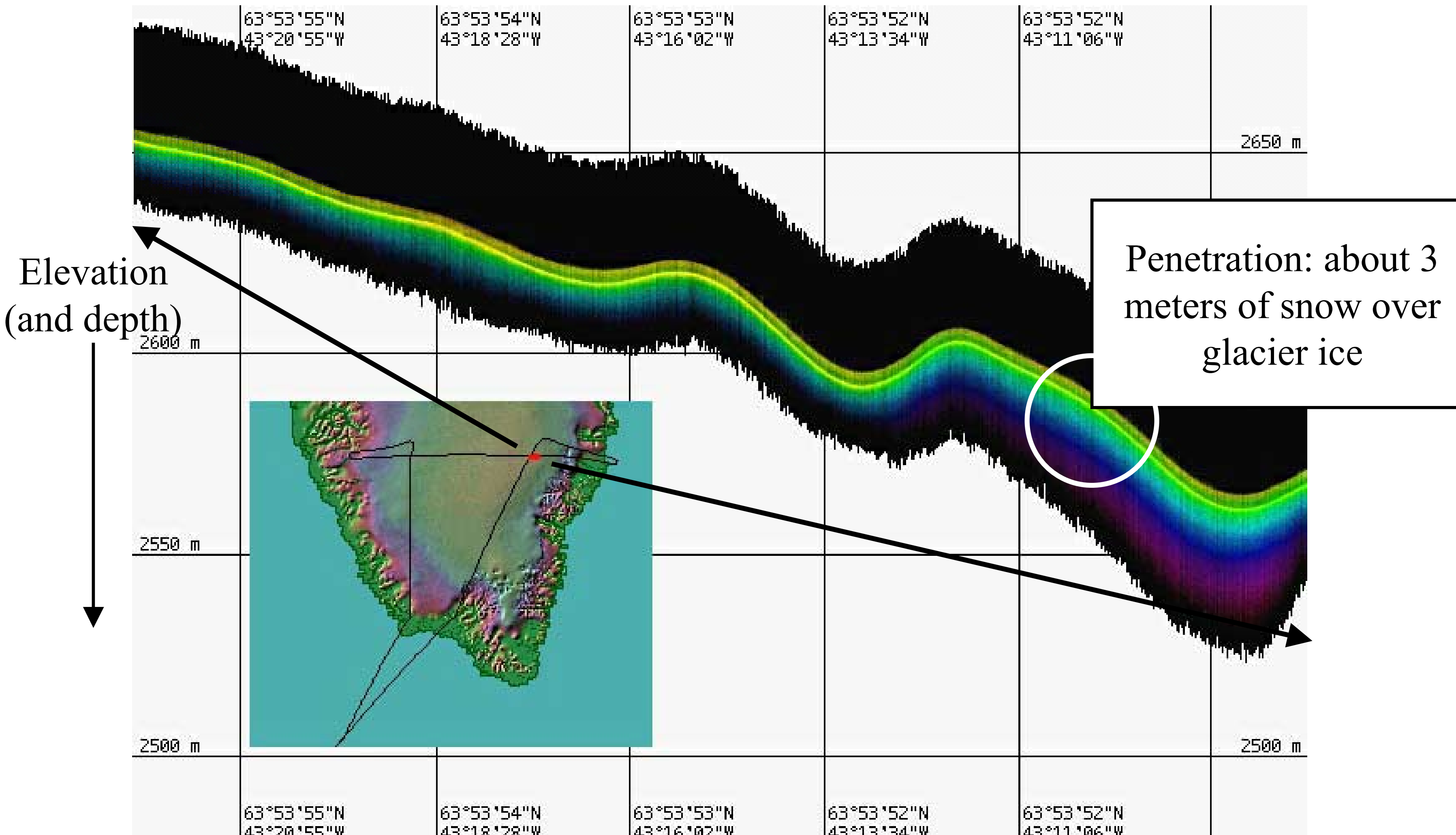
ATM & D2P: Snow-covered land ice



NB: Subsurface returns enhanced to show layers at depth

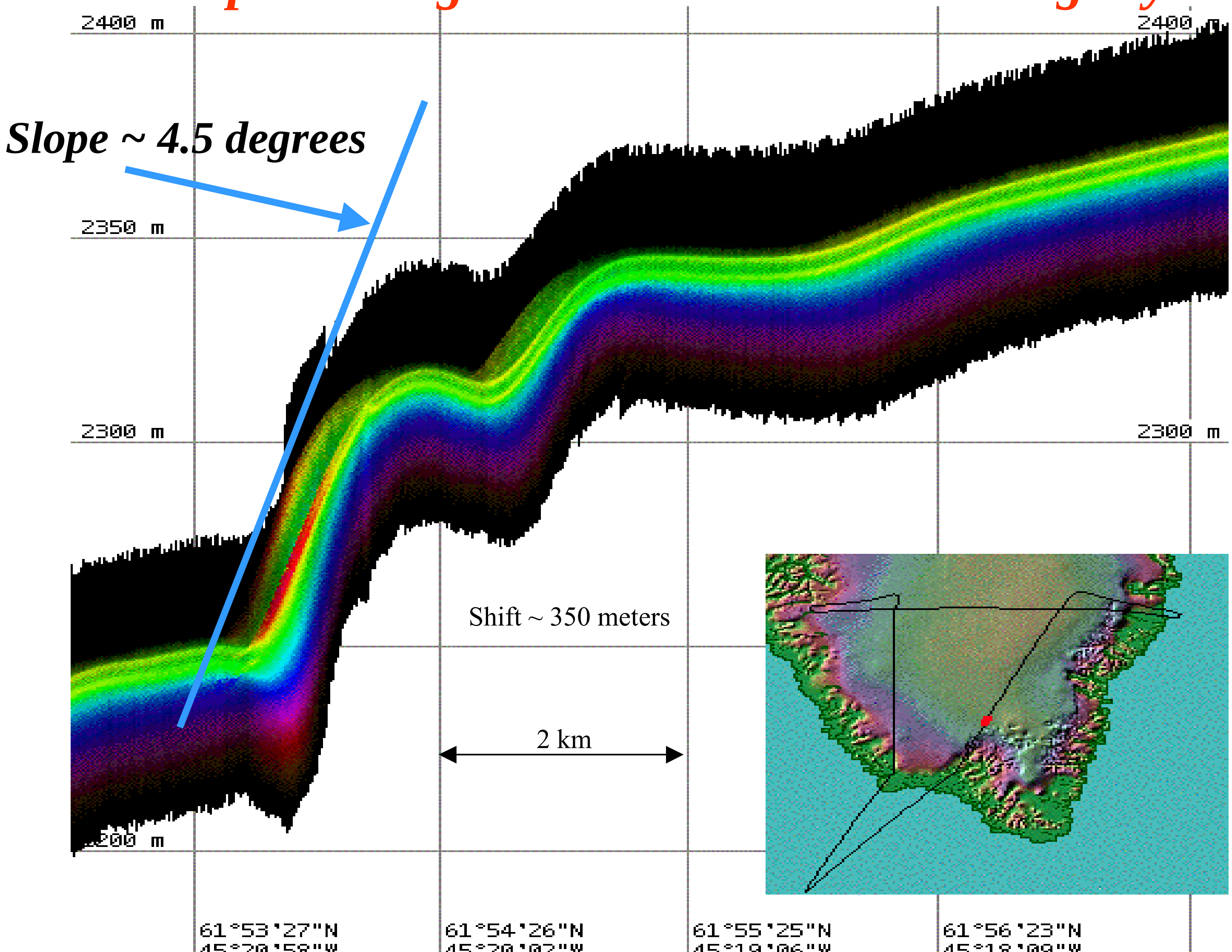
Greenland, Eastern Ice Cap

Extensive flight experience



Doppler Ambiguity: *Example*

Slope > along-track beamwidth => ambiguity



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