Parameter Trade Study of Space-Based Coherent Doppler Lidar Wind Measurement Using NASA's 2006 Wind Mission Study Parameters

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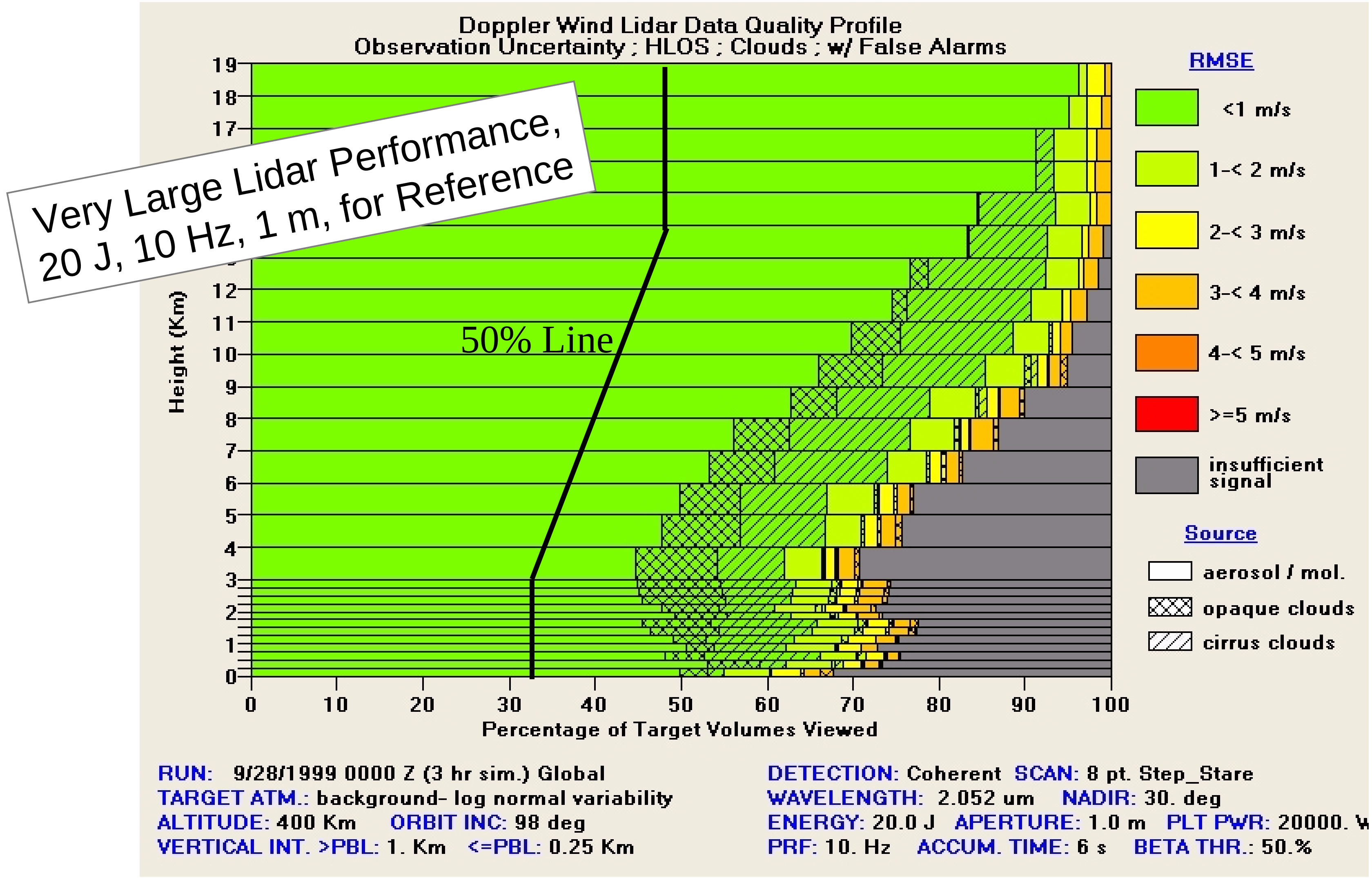
Nominal Mission Parameters

- Demo wind measurement requirements: 2 lines of horizontal wind profiles
- 2006 Wind Mission Study vertical resolution: 500/2000/3000
- 400 km, 45 deg nadir, 4 azimuth angles
- 0.25 J, 5 Hz, 0.5 m, no nadir angle collection loss, 2.053 microns, 180 ns
- 3 dB misalignment loss, no SNR reserve, no unexplained loss
- 20 m/s full LOS processing search bandwidth, last pass through data
- LSE = 11.5% not including misalignment loss; 5.8% with misalignment loss
- 60 shot accumulation attempted; 12 s; 85.2 km
- Assume 1.5 s to change azimuth angle
- Pattern repeat = 4 x (12 + 1.5) = 54 s = 390 km
- 0.14 km^{-1} cloud layer at 9-10 km (GTWS requirement)
- 2-3 km cloud layer blocks half of lidar shots (GTWS requirement)
- Aerosol backscatter profiles: background and enhanced; 50^{th} percentile (GTWS requirement)
- No vertical shear of horizontal wind velocity; always aligned with beam (broadens signal spectrum)
- 1 m/s design 1-σ wind turbulence (broadens signal spectrum)
- 0.5 m/s 1-σ laser difference frequency knowledge error
- Sampling/representativeness error = 0.67 m/s (85 km line in 100 km box)

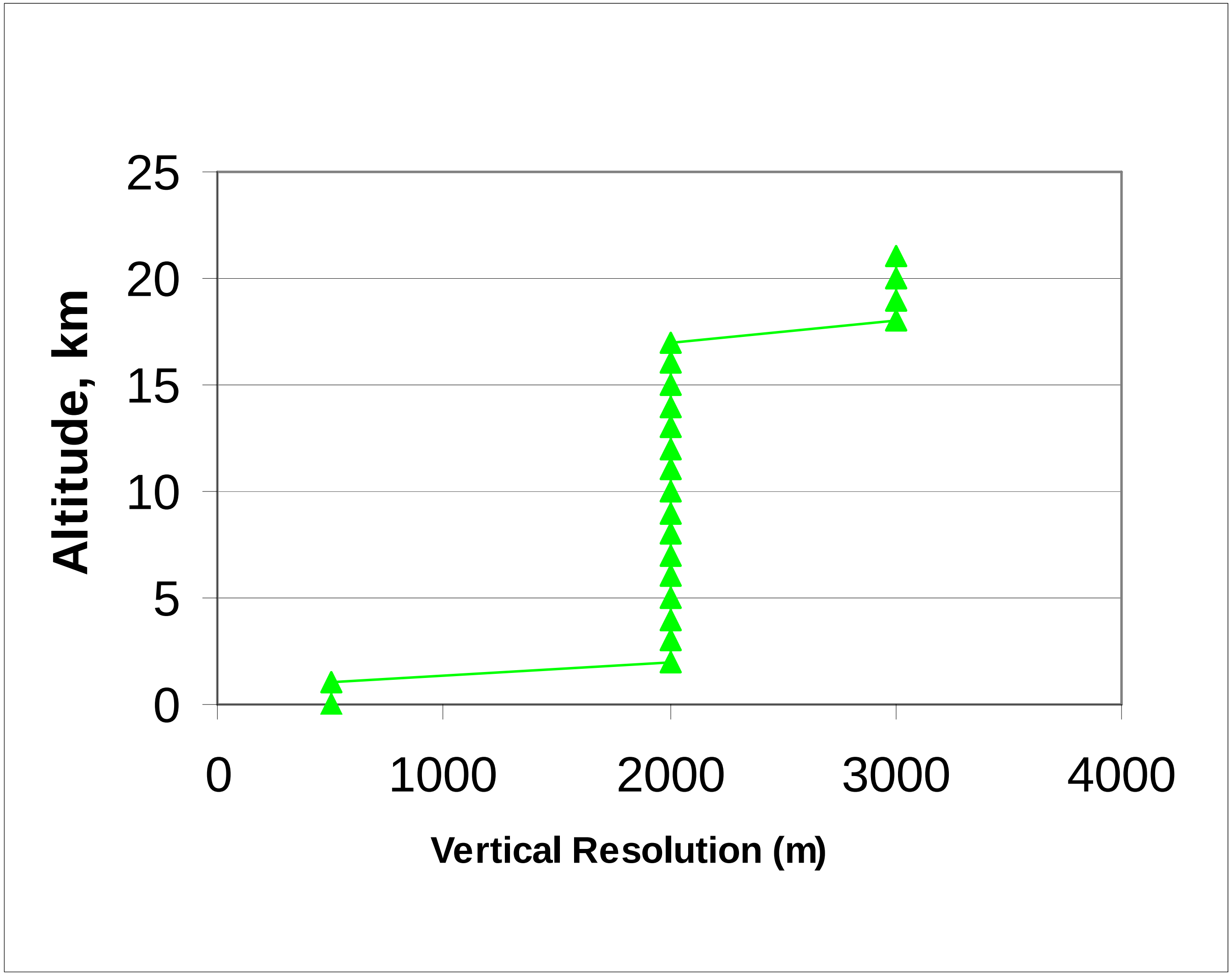
Origin of Success Percentage Requirement Profile



Courtesy Dr. G. David Emmitt

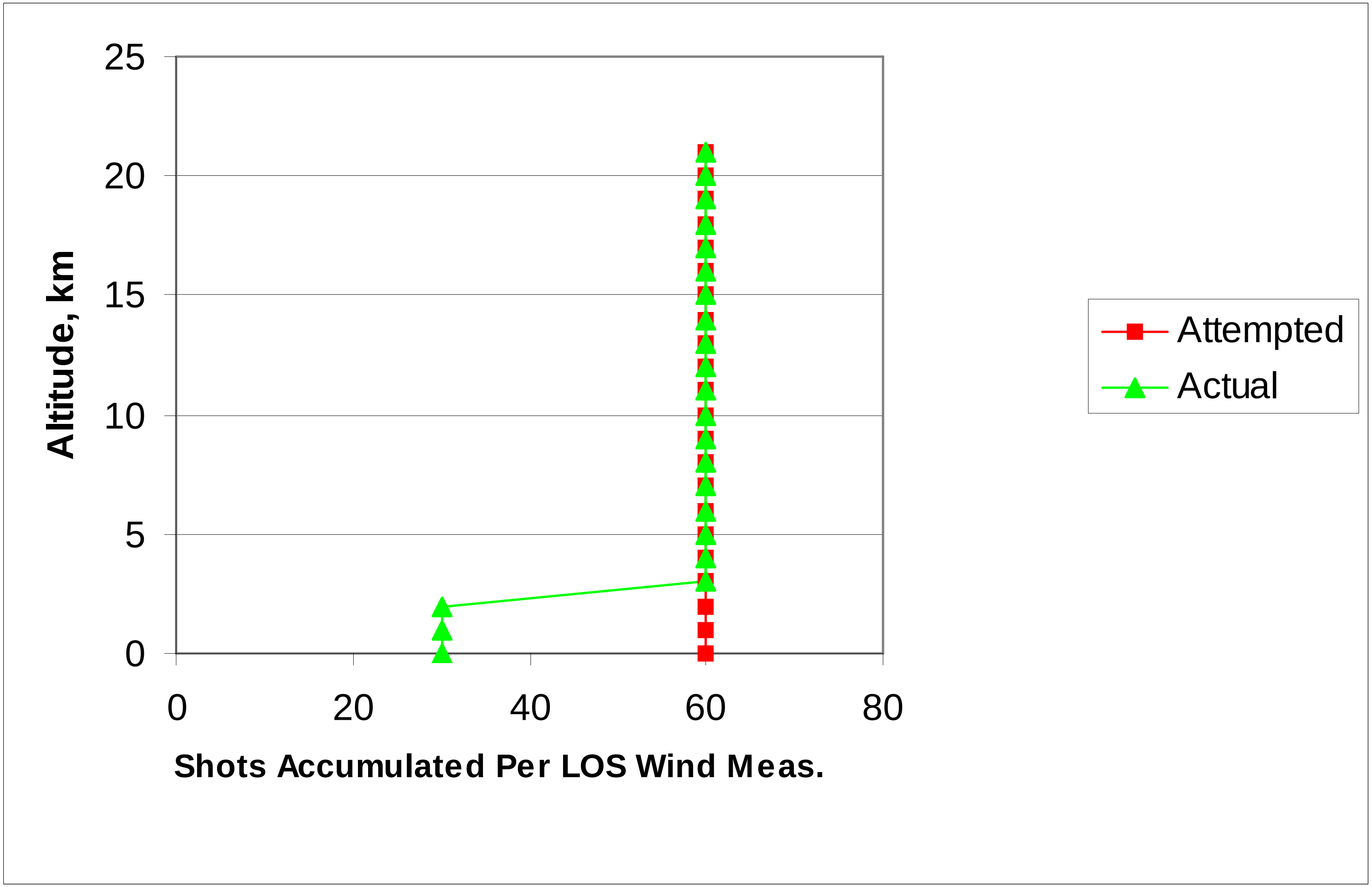
- Requirements call for >50% success rate after cloud blockage effects (gray area above)
- Error (RMSE) is LOS projected to horizontal direction incl. atmosphere, then incl. horizontal sampling error

Vertical Resolution Requirement

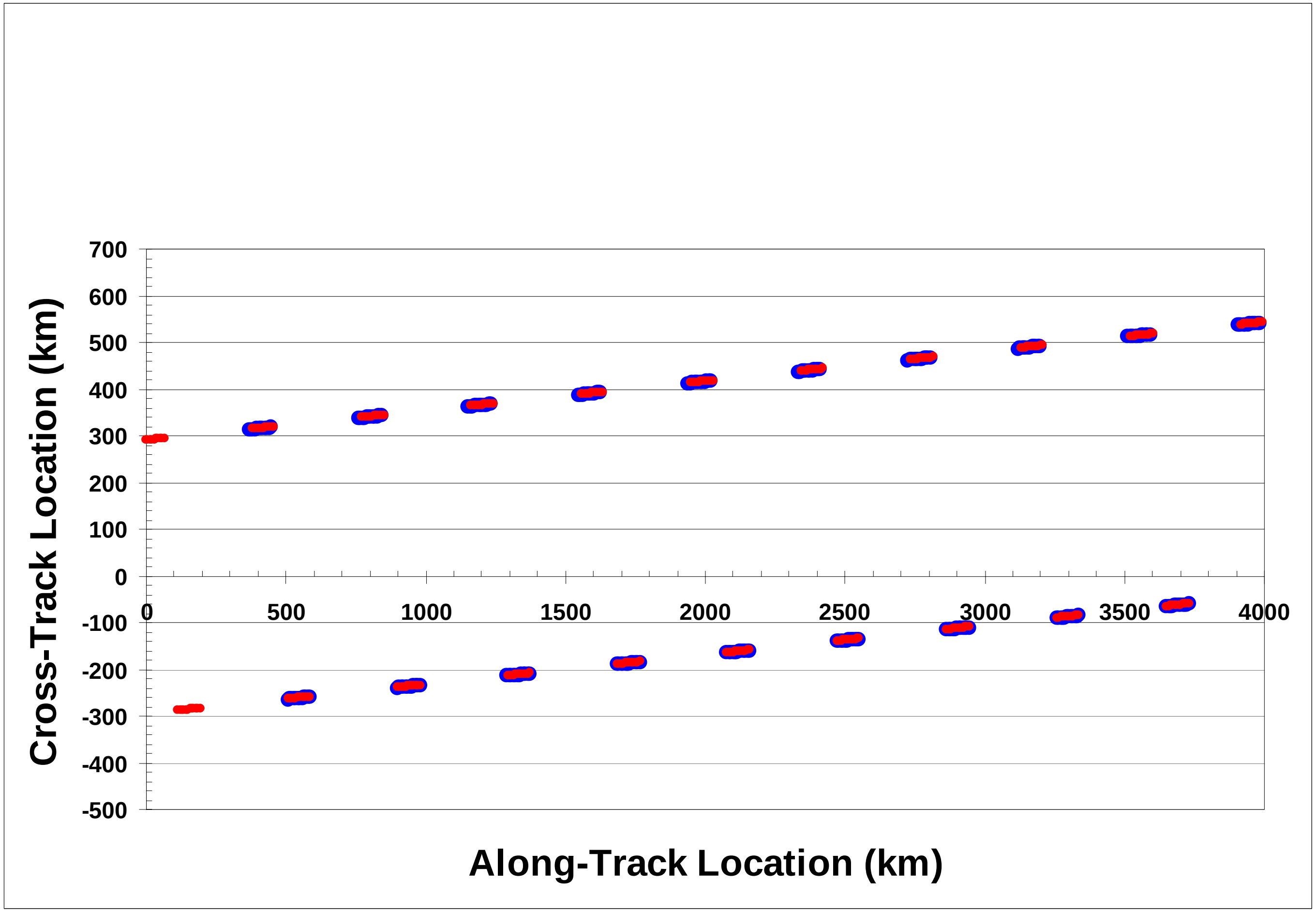


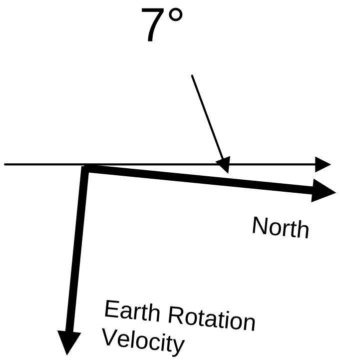
Shot Accumulation

12 s to accumulate, 1.5 s to move



Scan Pattern
400 km orbit, 45° nadir angle, 0° latitude
311, 41, 222, 132°
12 s to accumulate, 1.5 s to move





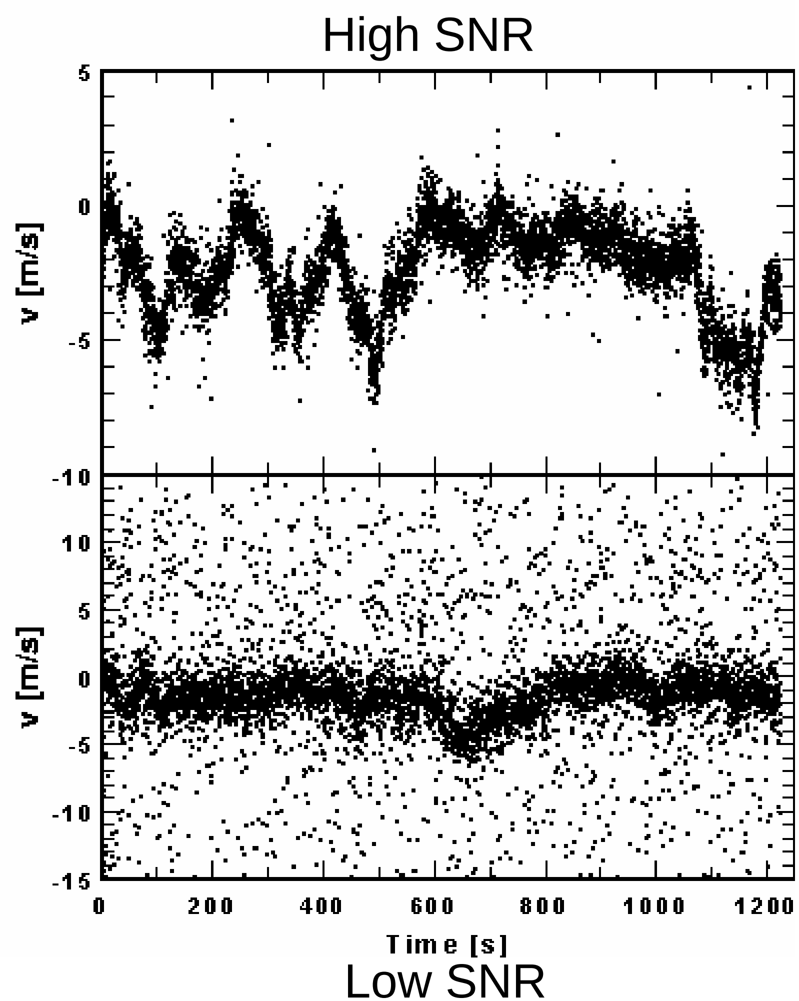
Two Parameters Required to Describe Wind Measurement Performance of Coherent Doppler Lidar

1. Pr{good}, the “probability of a good wind estimate”. Since coherent Doppler lidar is similar to tone detection in noise, when the signal is found above the noise, the frequency/velocity estimate is very accurate. When a noise peak is mistakenly chosen as the signal, the velocity estimate is random over the search space. For fixed conditions, repeated attempts to measure the wind at a particular range gate will produce a group of good wind estimates, and a group of random numbers.

2. The velocity accuracy (error) of the “good” wind estimates

Rod Frehlich, Stephen Hannon, Sammy Henderson

J. Atmos. Oceanic. Tech. Vol. 11, 1517-1528, (1994)



Performance Theory

- Rod G. Frehlich, "*Velocity Error for Coherent Doppler Lidar with Pulse Accumulation*," J. Atmos. & Oceanic Tech. 21, 905-920 (June 2004),   Section 8 = User Manual
- Valid range of Ω = # independent samples per range gate = 0.25 – 32
- Valid range of Ω/M: < 0.2   (M = # complex lidar data points/range gate)
- Valid range of b = probability a velocity estimate is bad, Pr{bad}: 0.00001 – 0.7 (Valid range of Pr{good} = 0.99999 – 0.3)
- Note: velocity error is underestimated when b < 0.01 (per Frehlich)

Two Ways to Show Performance

1. Use the GTWS requirement "probability of a good wind estimate," Pr{good}, at all altitudes and compare the simulated aerosol backscatter coefficient (β) profile to the GTWS requirement profile. Simulated β lower than required β is a backscatter margin.

$$\Pr\{\text{good}\}_{\text{simulated}} = \Pr\{\text{good}\}_{\text{requirement}}$$

$$\beta_{\text{simulated}} \neq \beta_{\text{requirement}}$$

2. For altitudes where the simulated β is lower than the requirement β, reduce Pr{good} until the simulated β rises to equal the requirement β. Those altitudes then have a Pr{good} margin.

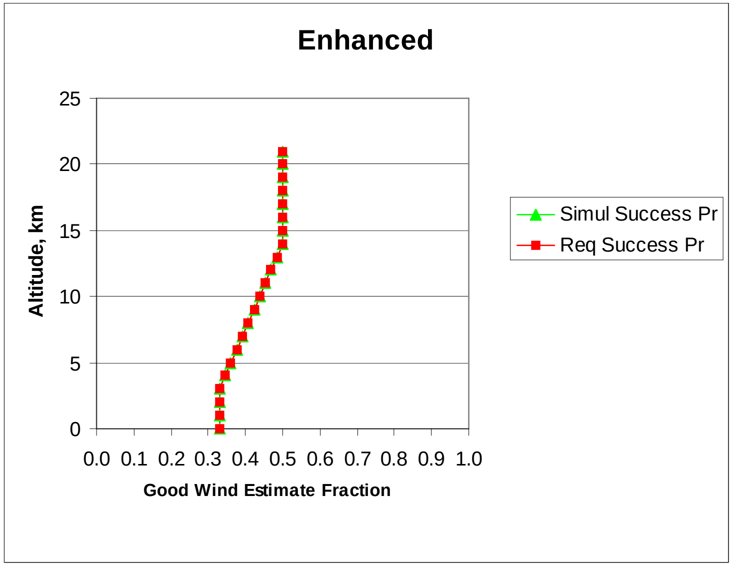
$$\beta_{\text{simulated}} = \beta_{\text{requirement}}$$

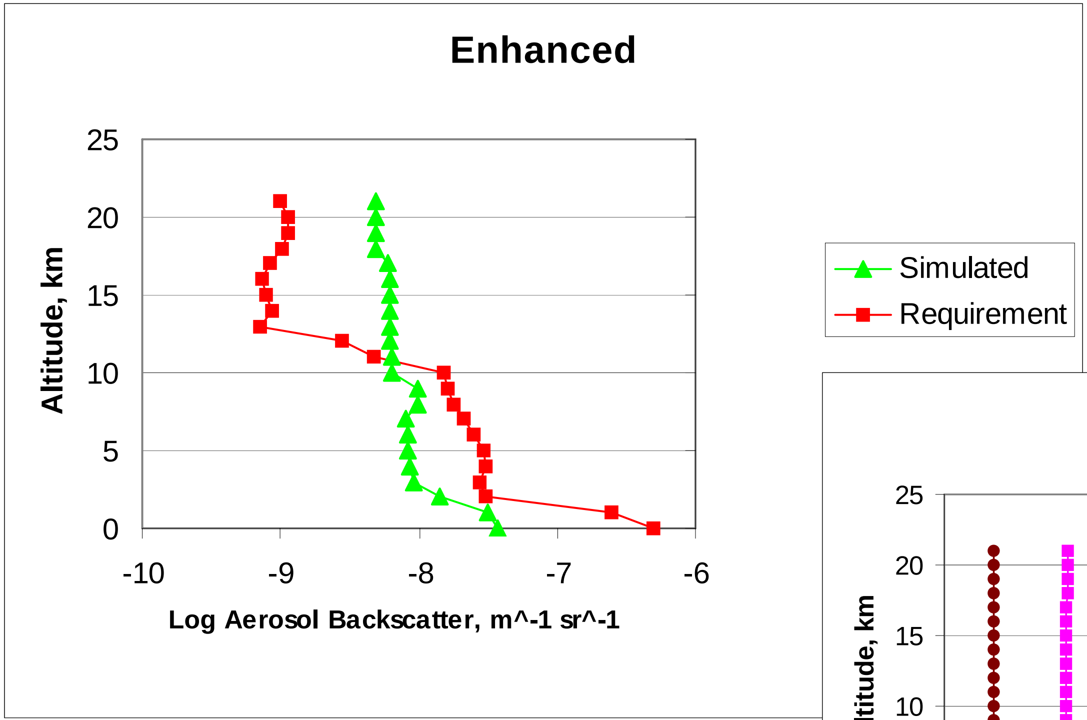
$$\Pr\{\text{good}\}_{\text{simulated}} > \Pr\{\text{good}\}_{\text{requirement}}$$

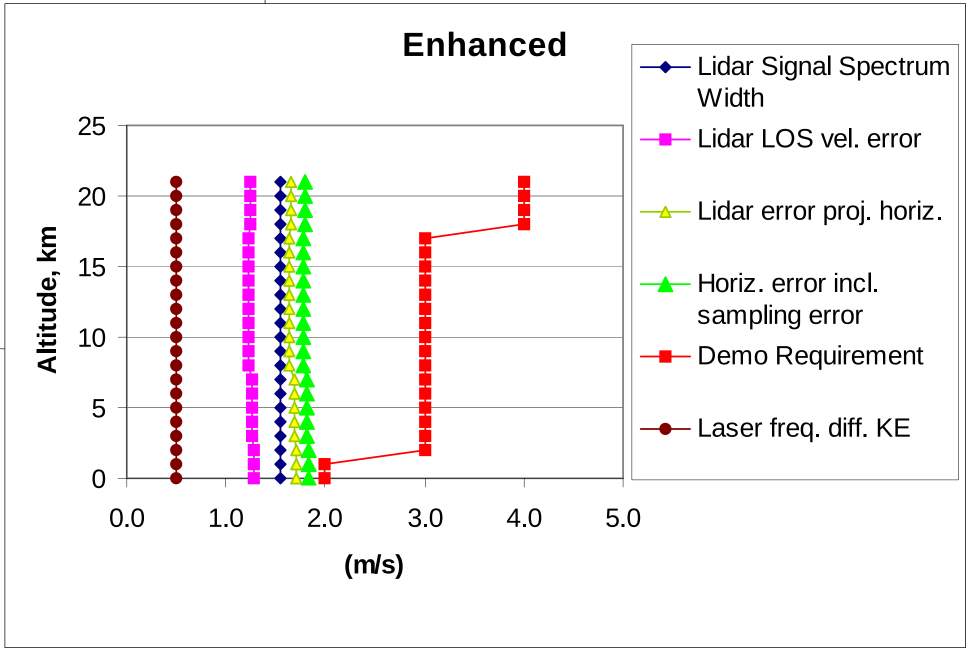
[Simulation limited to: 0.3 < Pr{good} < 1]

Performance Approach 1

$$Pr\{good\}_{simulated} = Pr\{good\}_{requirement}$$



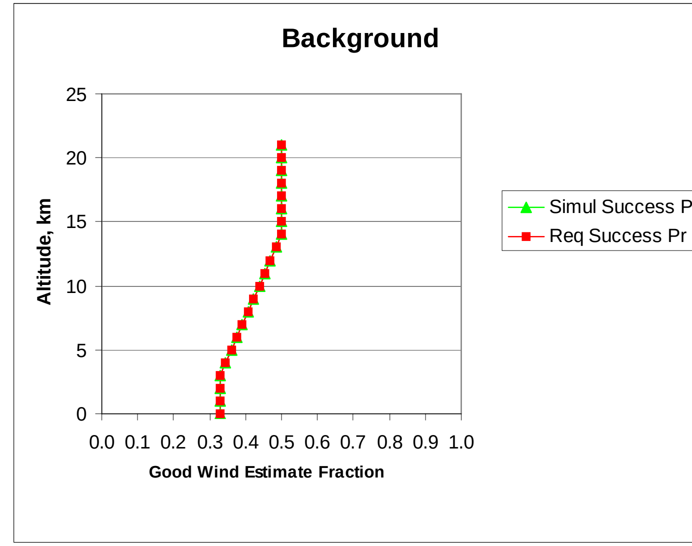


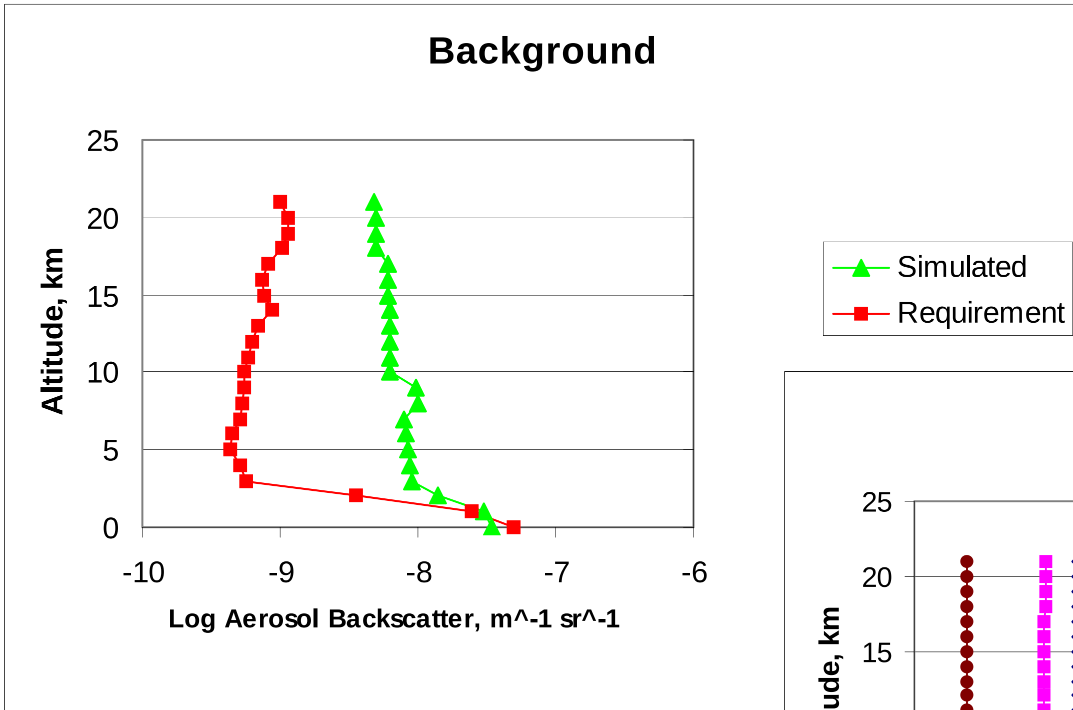


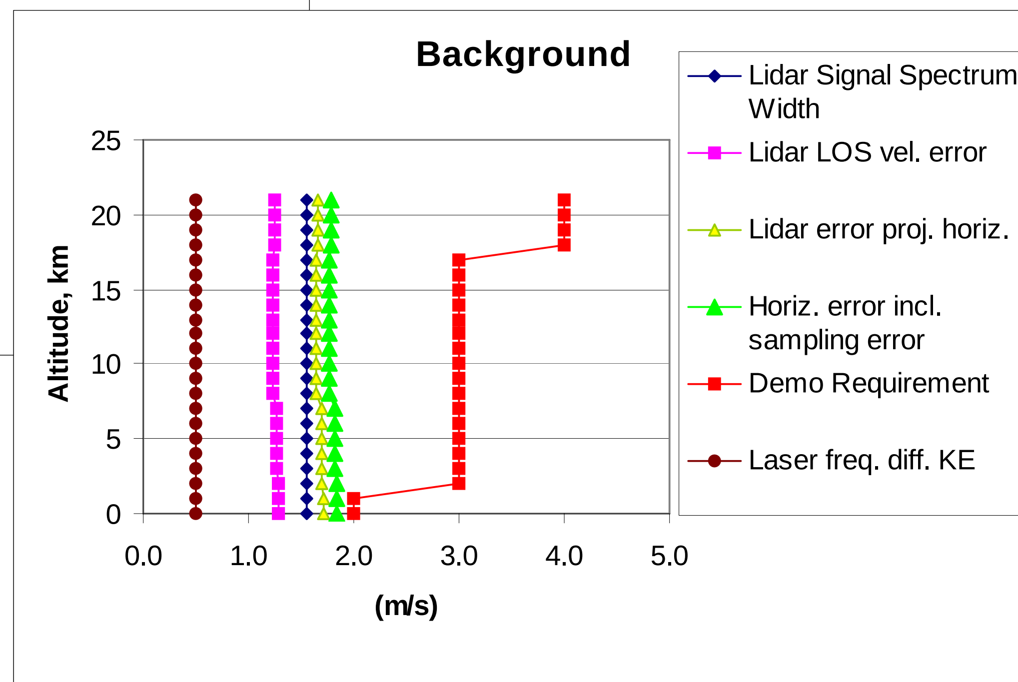
- ➢ Aerosol backscatter adequate to 11 km, with margin
- ➢ Excellent velocity accuracy meets requirement

Performance Approach 1

$Pr\{good\}_{simulated} = Pr\{good\}_{requirement}$



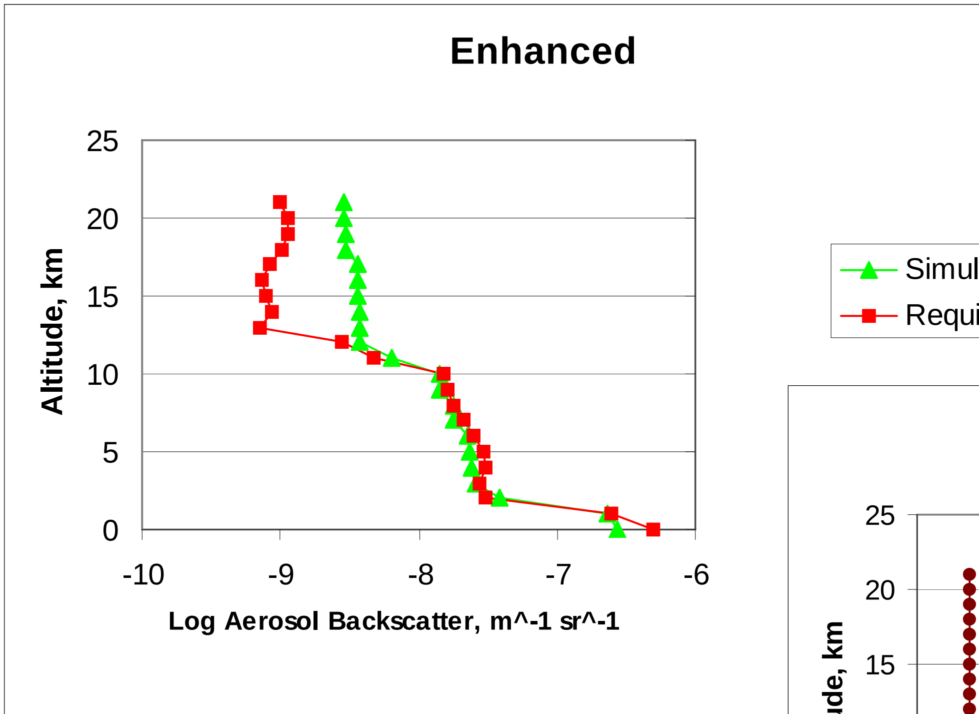


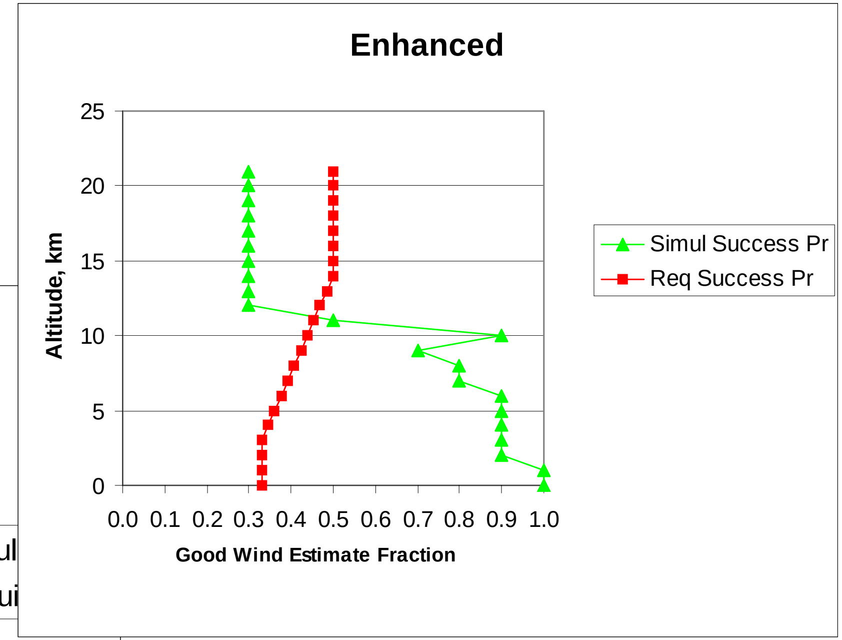


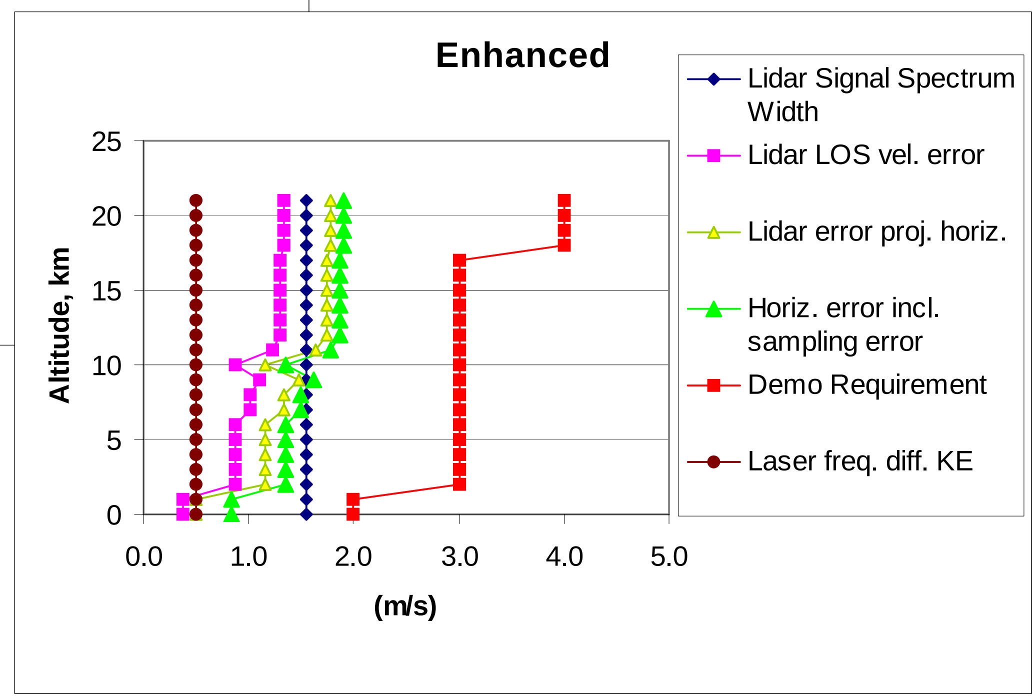
- ➢ Aerosol backscatter inadequate above 1 km
- ➢ Adequate velocity accuracy for “good” measurements

Performance Approach 2

$Pr\{good\}_{simulated} > Pr\{good\}_{requirement}$



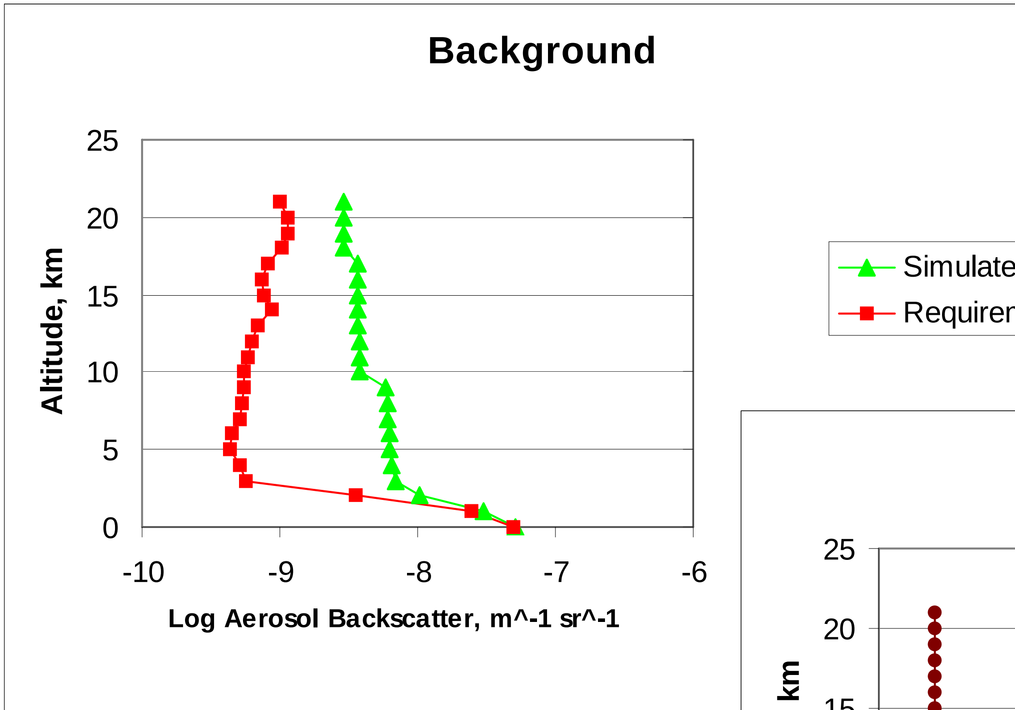


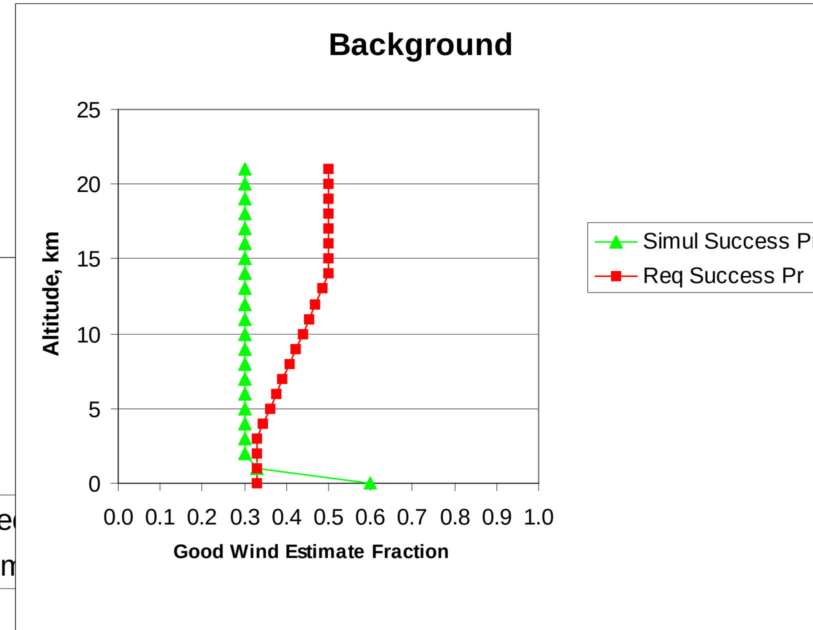


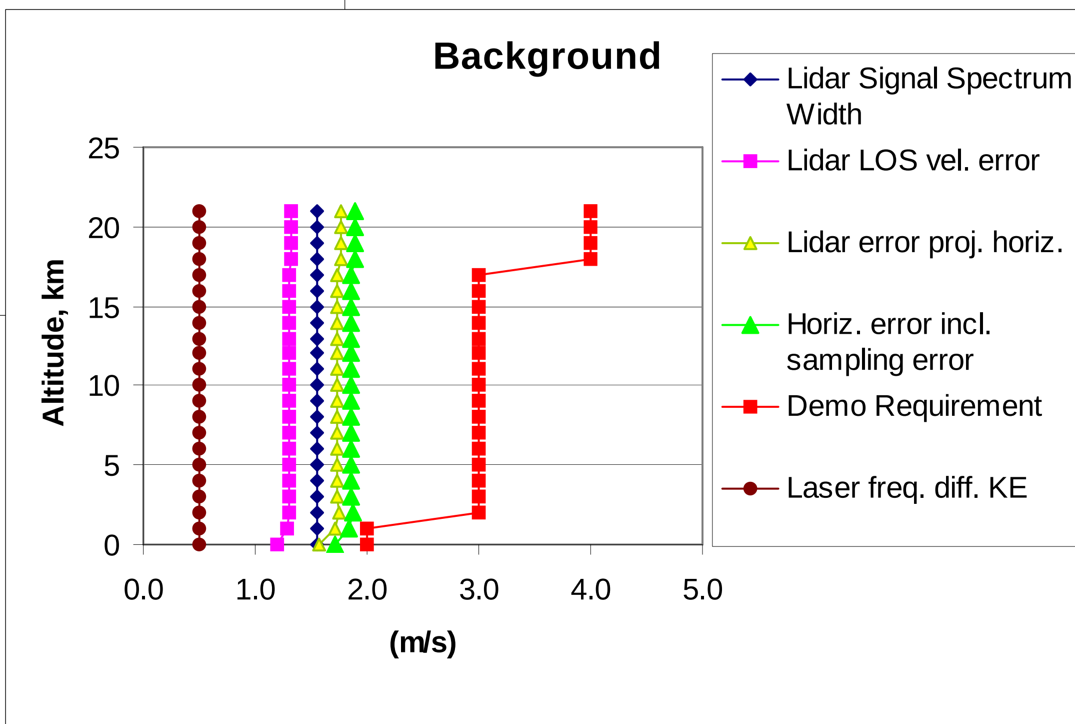
- Pr{good} > 0.8 to 8 km
- Excellent velocity accuracy meets requirement

Performance Approach 2

$Pr\{good\}_{simulated} > Pr\{good\}_{requirement}$



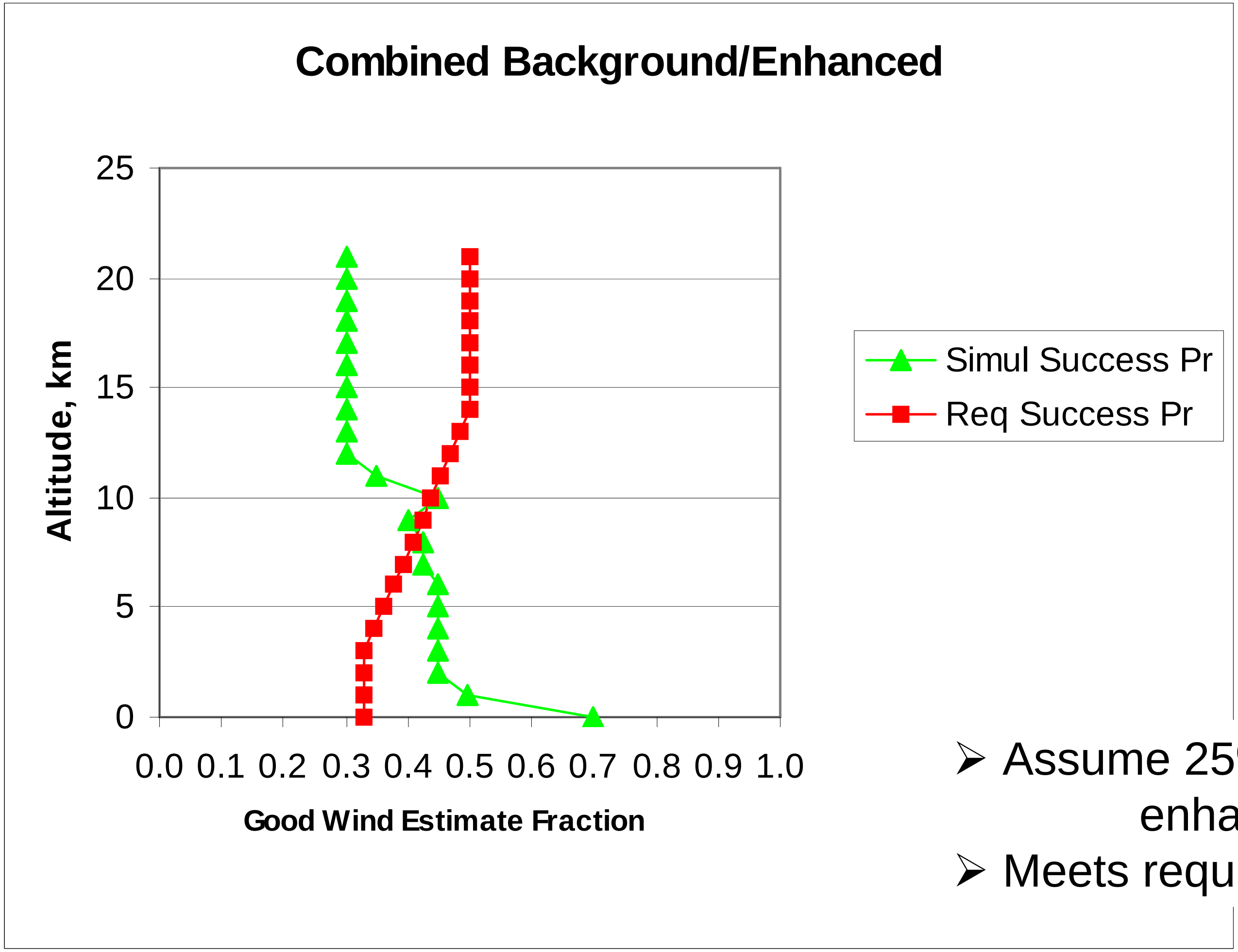




- ➢ Inadequate performance above 1 km
- ➢ Adequate velocity accuracy for “good” measurements

Performance Approach 2

$Pr\{good\}_{simulated} > Pr\{good\}_{requirement}$



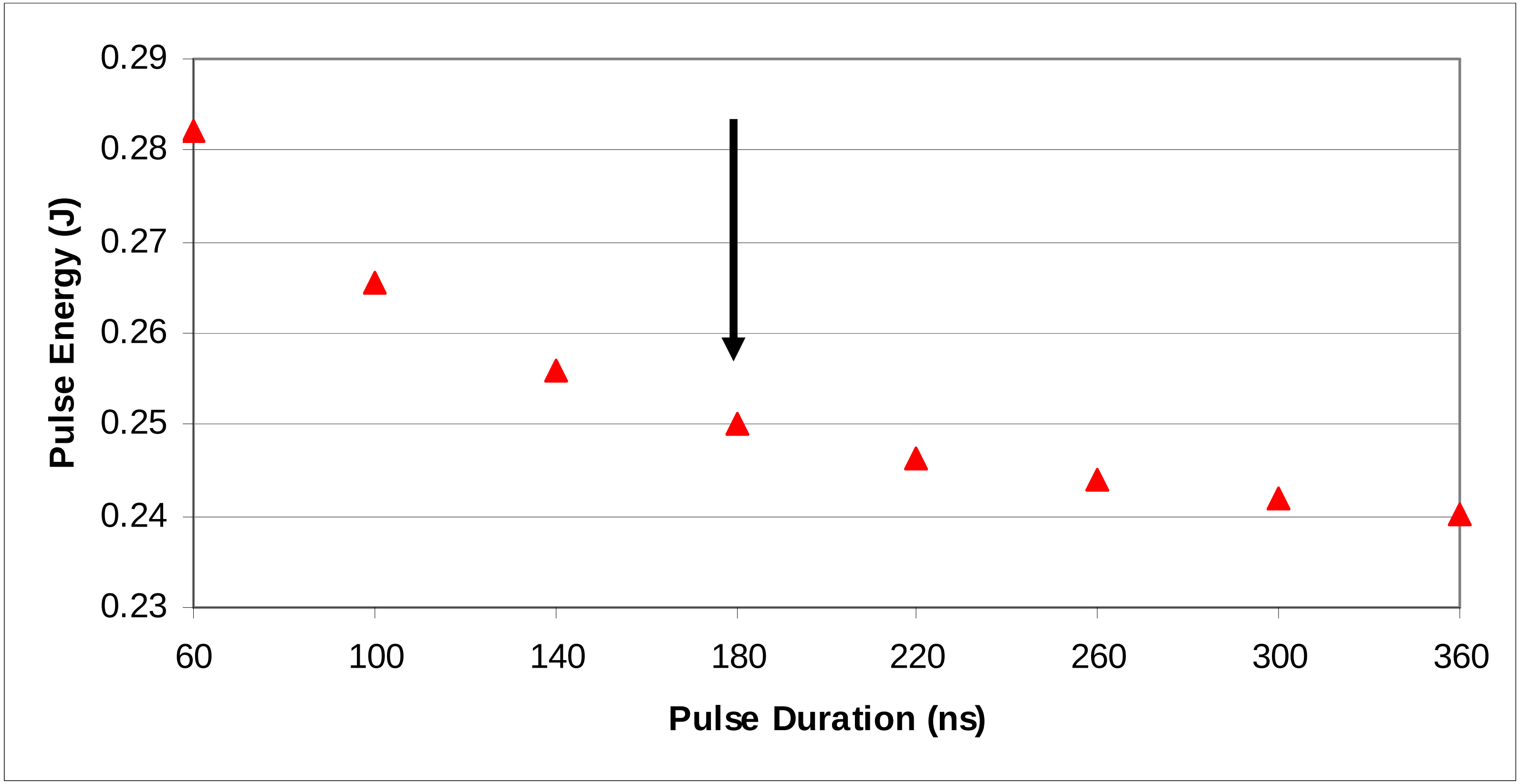
- Assume 25% of earth is enhanced aerosols
- Meets requirements up to 8 km

Lidar Parameter Trade Study: Conditions of Low But Adequate SNR

- 3 dB 1-σ transmit/receive misalignment loss (1-σ angle = 3.082 μrad)
- 180 ns pulse duration FWHM
- 11 km altitude
- Enhanced aerosol levels; β = 4.8 x 10-9 $m^{-1}sr^{-1}$
- Vertical resolution = 2000 m
- M = 393.1 (# complex lidar data points/range gate)
- Ω = 30.4 (# independent samples per range gate)
- φ = 1.725 (# coherent photoelectrons per range gate per shot)
- 60 shots accumulated
- Pr{good} = 0.5
- g/w_{eff} = 0.80
- Lidar LOS velocity error = 1.23 m/s
- Total velocity error projected to horizontal w/sampling error = 1.77 m/s

Pulse Duration vs. Pulse Energy

- Assume no vertical wind shear; Assume no wind turbulence
- Assume no laser frequency difference error; Neglect effect on range resolution
- Hold Pr{good} constant



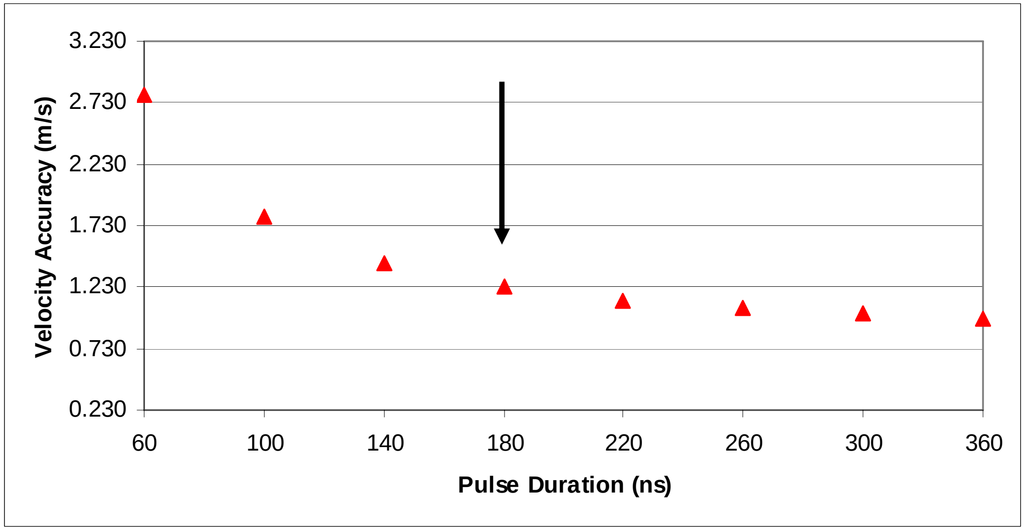
→ (nominal operating point)

What is happening to the velocity accuracy? ⇒

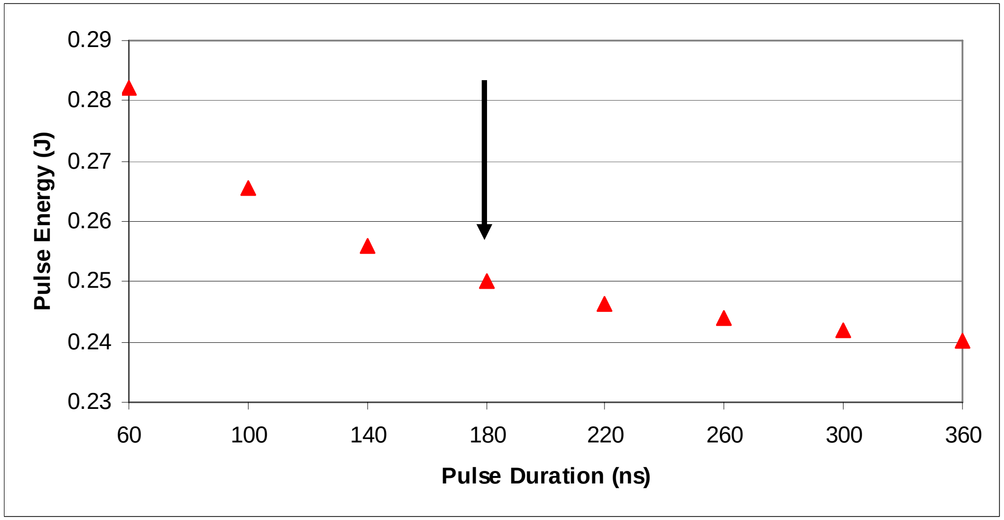
Pulse Duration vs. Velocity Accuracy

- Assume no vertical wind shear; Assume no wind turbulence
- Assume no laser frequency difference error; Neglect effect on range resolution
- Hold Pr{good} constant

Velocity Accuracy

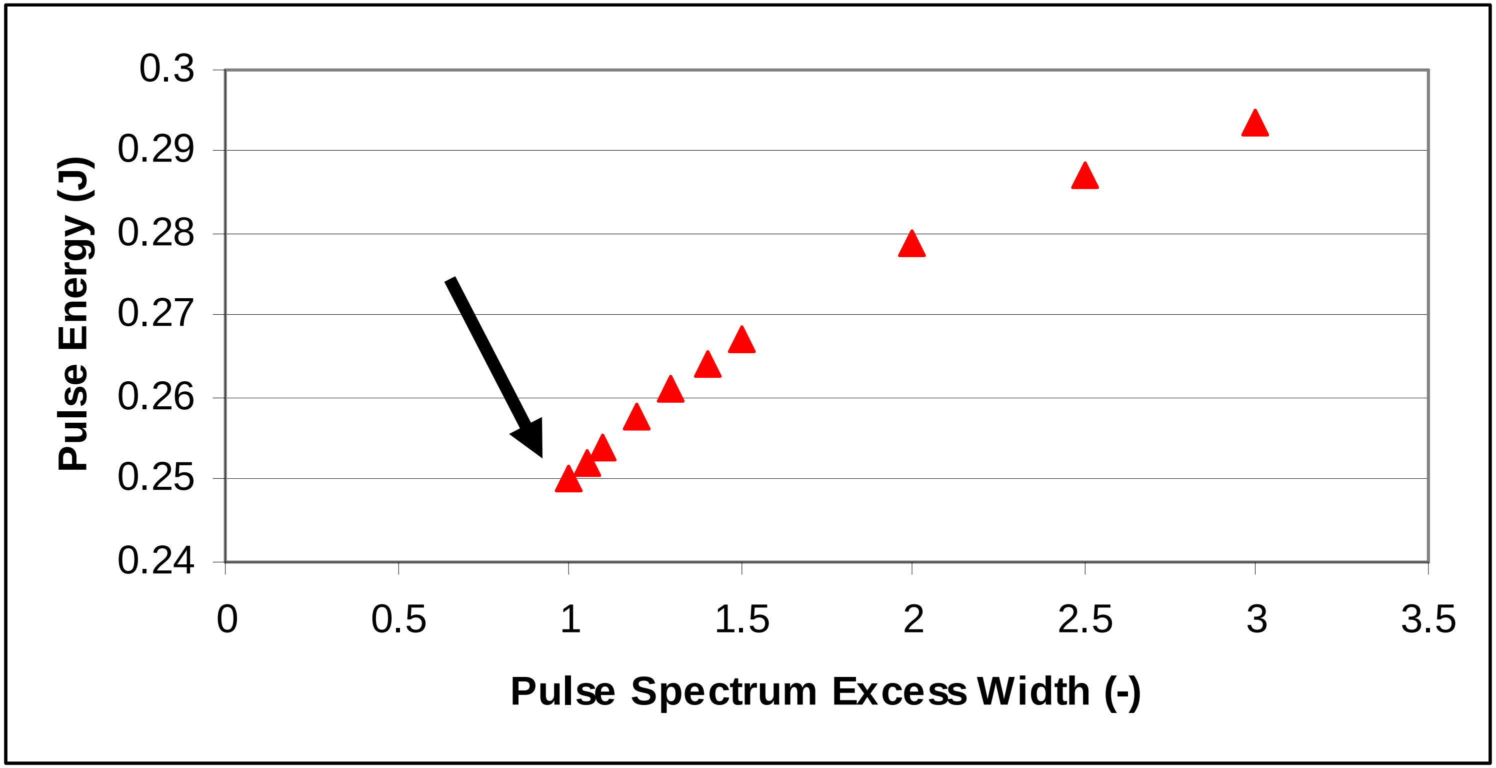


Pulse Energy



Spectrum Excess Width vs. Pulse Energy

- Hold Pr{good} constant



Above 1.05 is out of valid simulation range

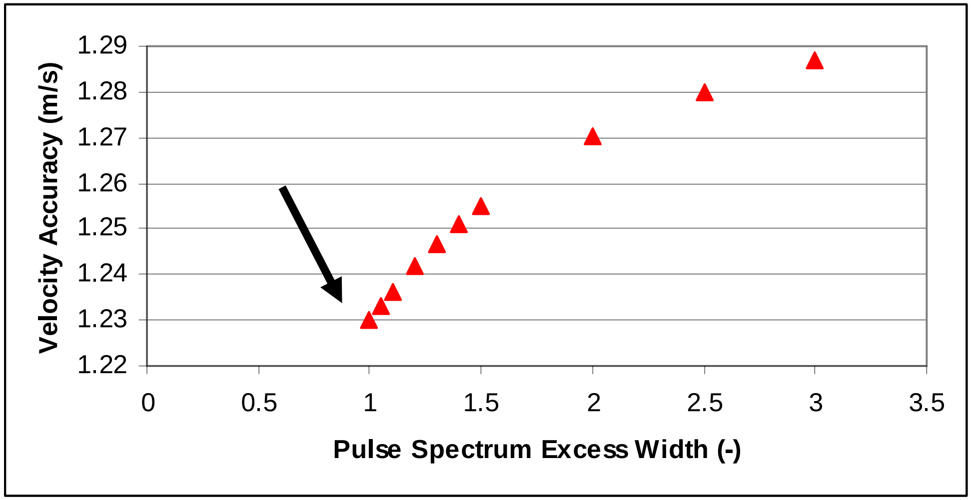
 (nominal operating point)

What is happening to the velocity accuracy? ⇒

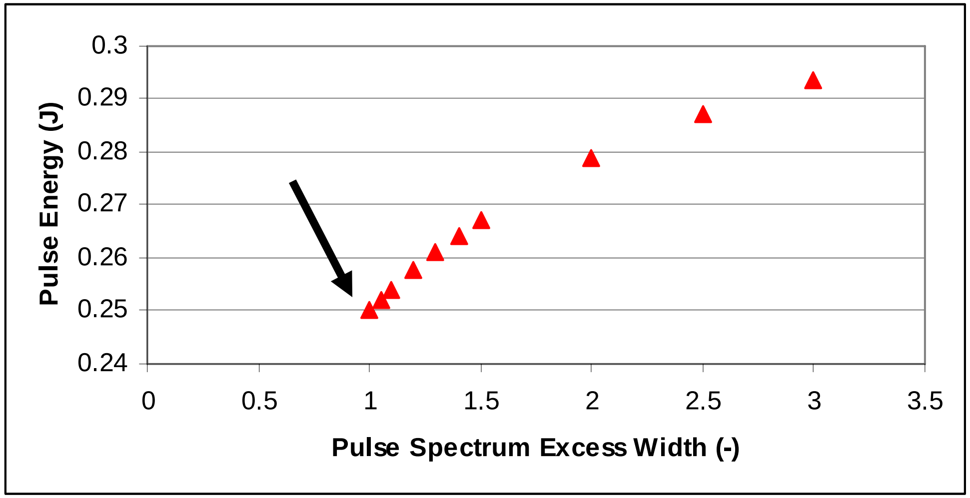
Spectrum Excess Width vs. Velocity Accuracy

- Hold Pr{good} constant

Velocity Accuracy



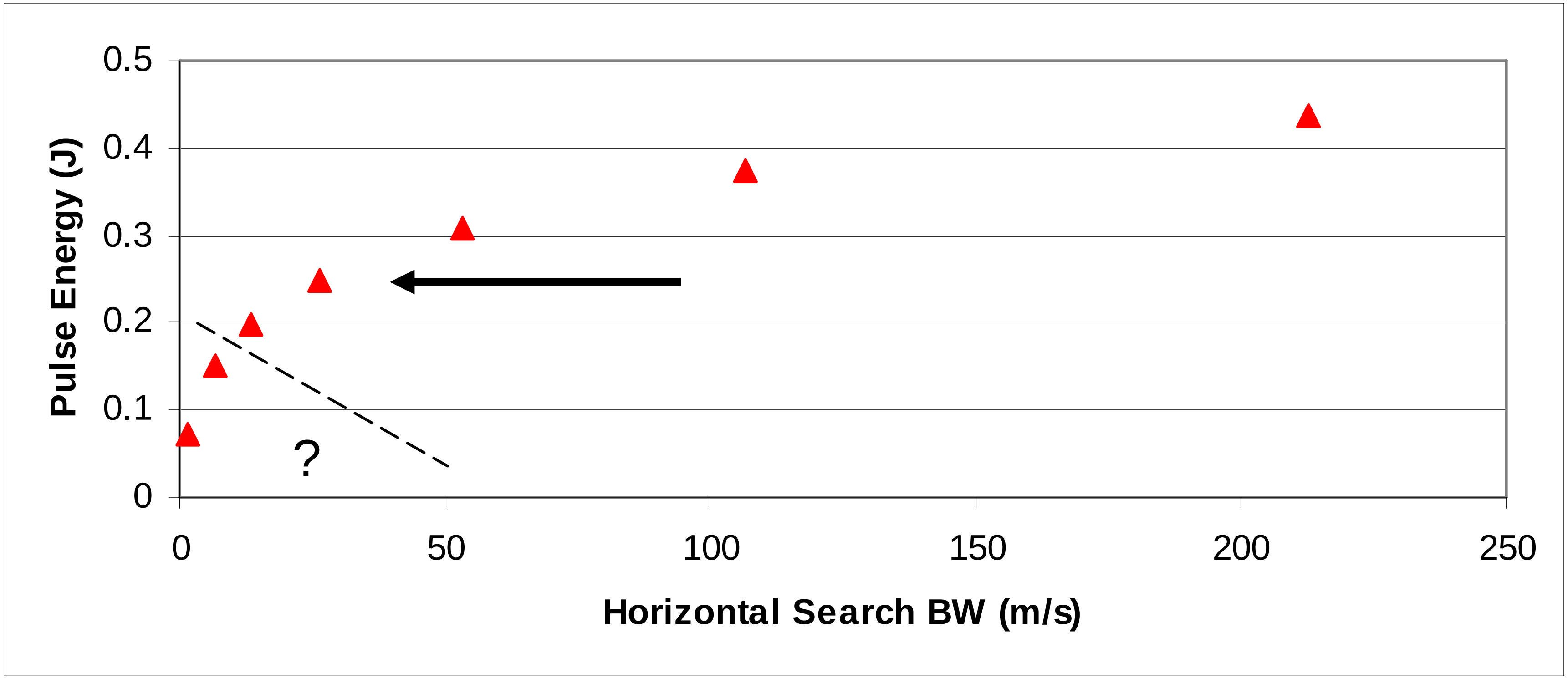
Pulse Energy



Above 1.05 is out of valid simulation range

Velocity Search Bandwidth vs. Pulse Energy

- Full search bandwidth in horizontal direction for last pass through the data
- Hold Pr{good} constant



What is happening to the velocity accuracy? ⇒

? = Outside the parameter limits of the simulation

Velocity Search Bandwidth vs. Velocity Accuracy

- Full search bandwidth in horizontal direction for last pass through the data
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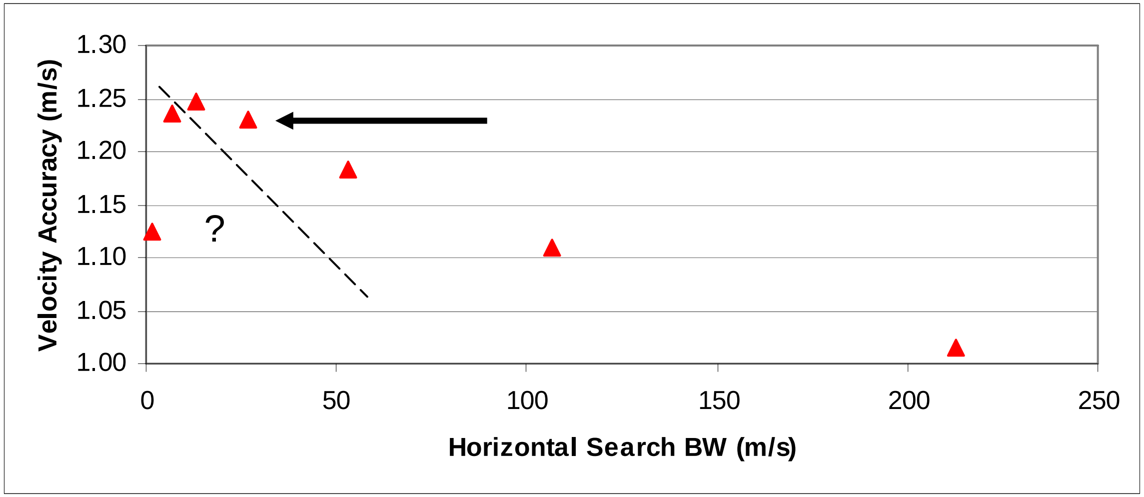
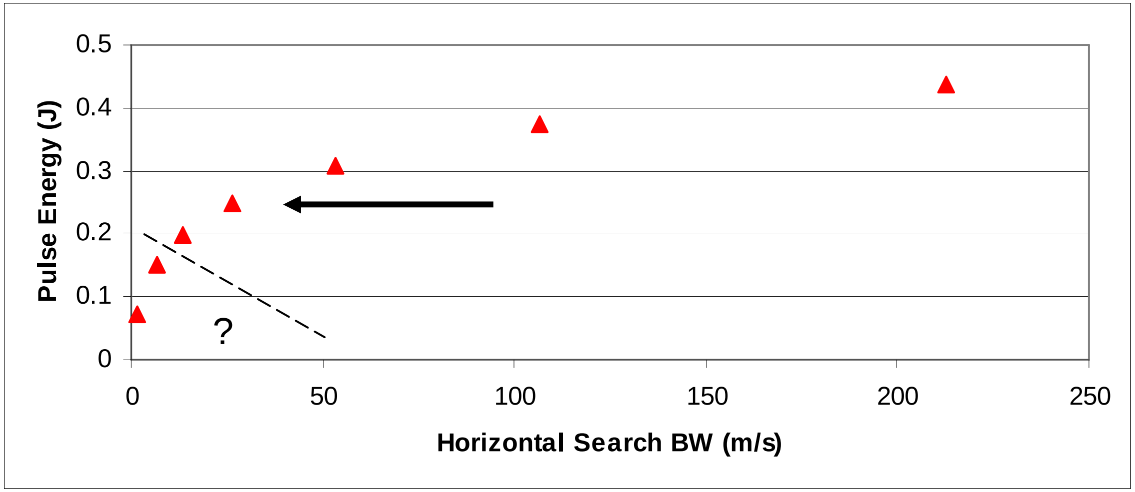
Velocity Accuracy



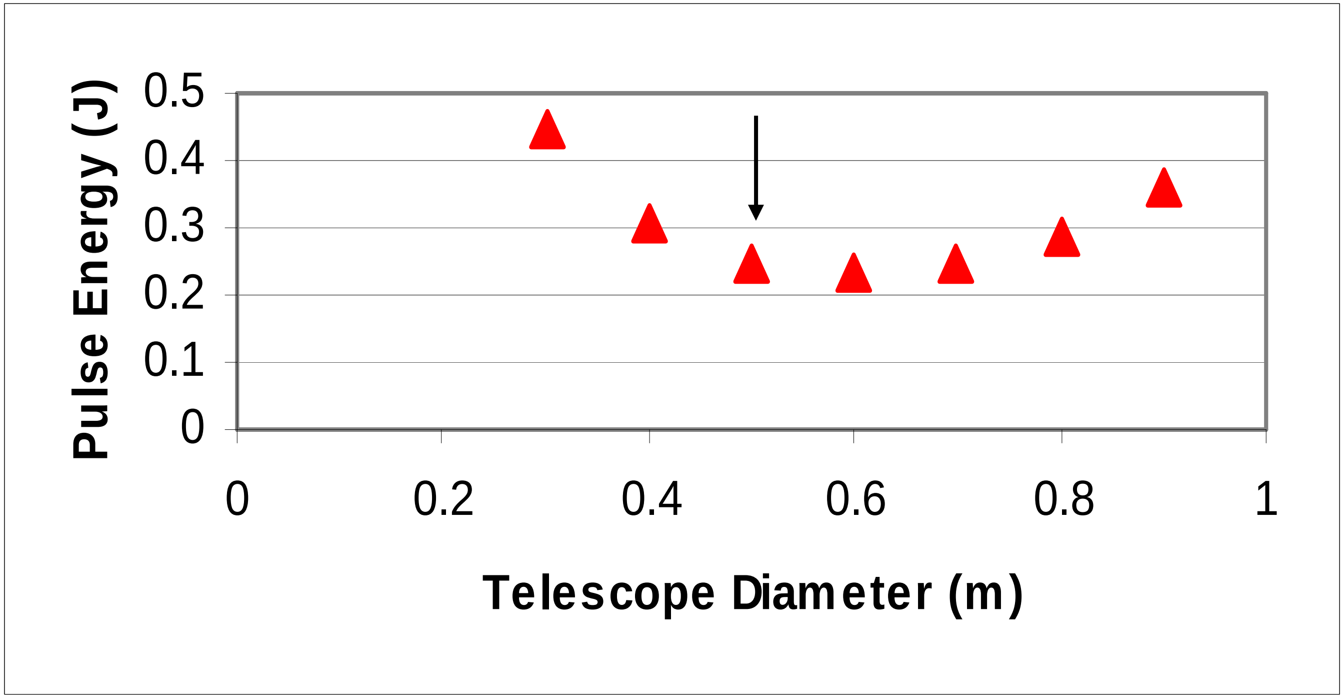
Pulse Energy



? = Outside the parameter limits of the simulation

Telescope Diameter vs. Pulse Energy

- Assume scanner does not reduce collection area
- Assume 1-σ transmit/receive misalignment angle fixed at 3.082 μrad
- Hold Pr{good} and velocity accuracy constant

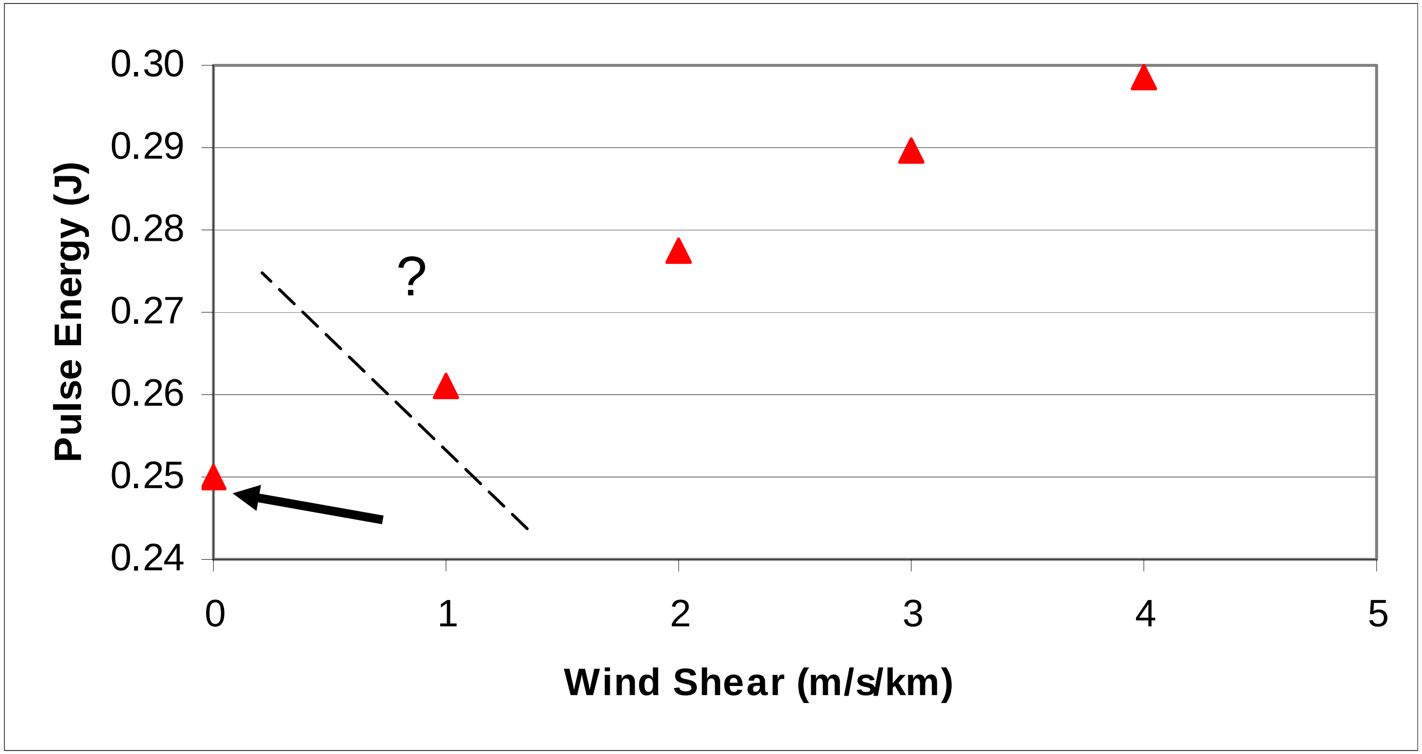


- Larger diameters have more SNR loss for fixed misalignment angle

→ (nominal operating point)

Wind Shear vs. Pulse Energy

- Vertical shear of horizontal velocity (always aligned with beam)
- Horizontal velocity always aligned with laser beam
- Hold Pr{good} constant
- Plot depends strongly on vertical resolution!



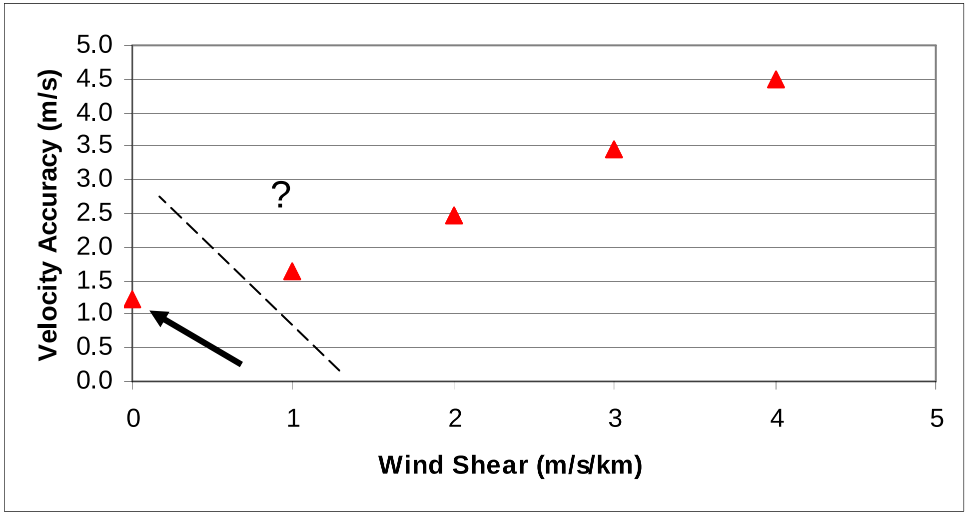
? = Outside the parameter limits of the underlying theory

→ (nominal operating point)

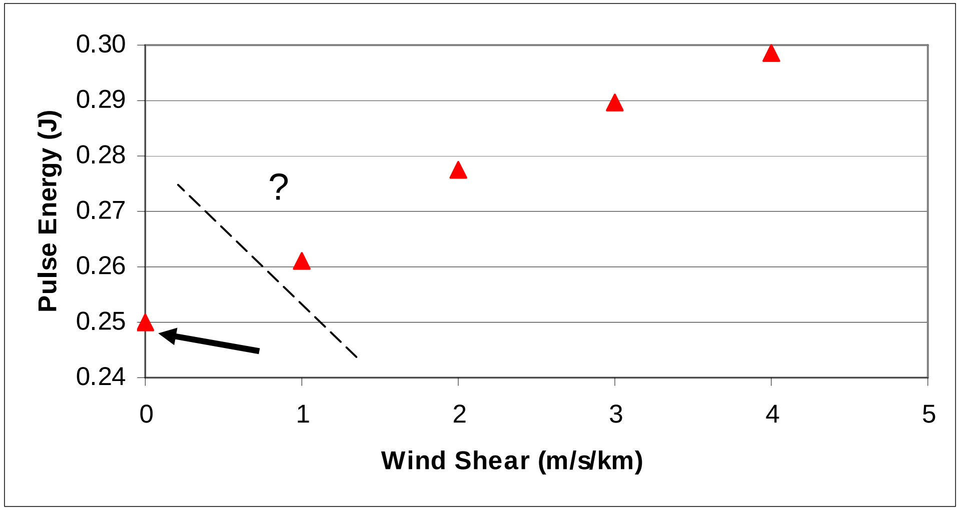
What is happening to the velocity accuracy? ⇒

Wind Shear vs. Velocity Accuracy

Velocity Accuracy



Pulse Energy

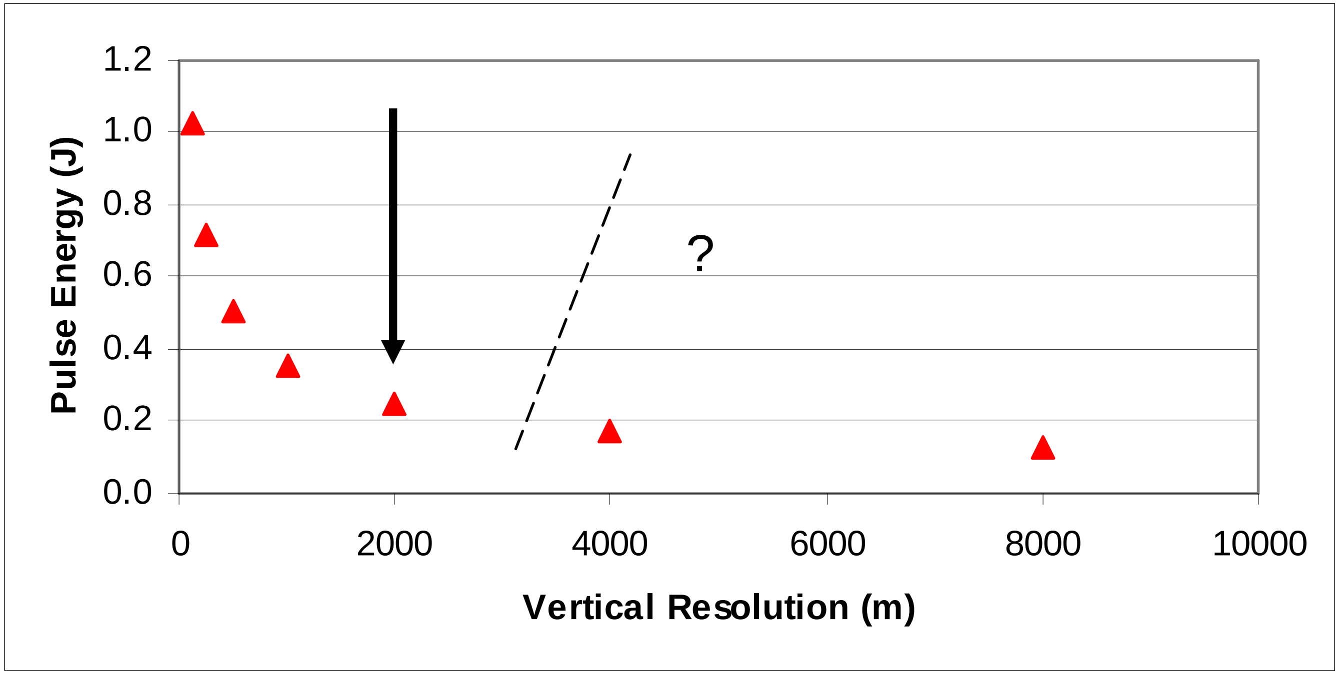


? = Outside the parameter limits of the underlying theory

(nominal operating point)

Vertical Resolution vs. Pulse Energy

- Hold Pr{good} constant

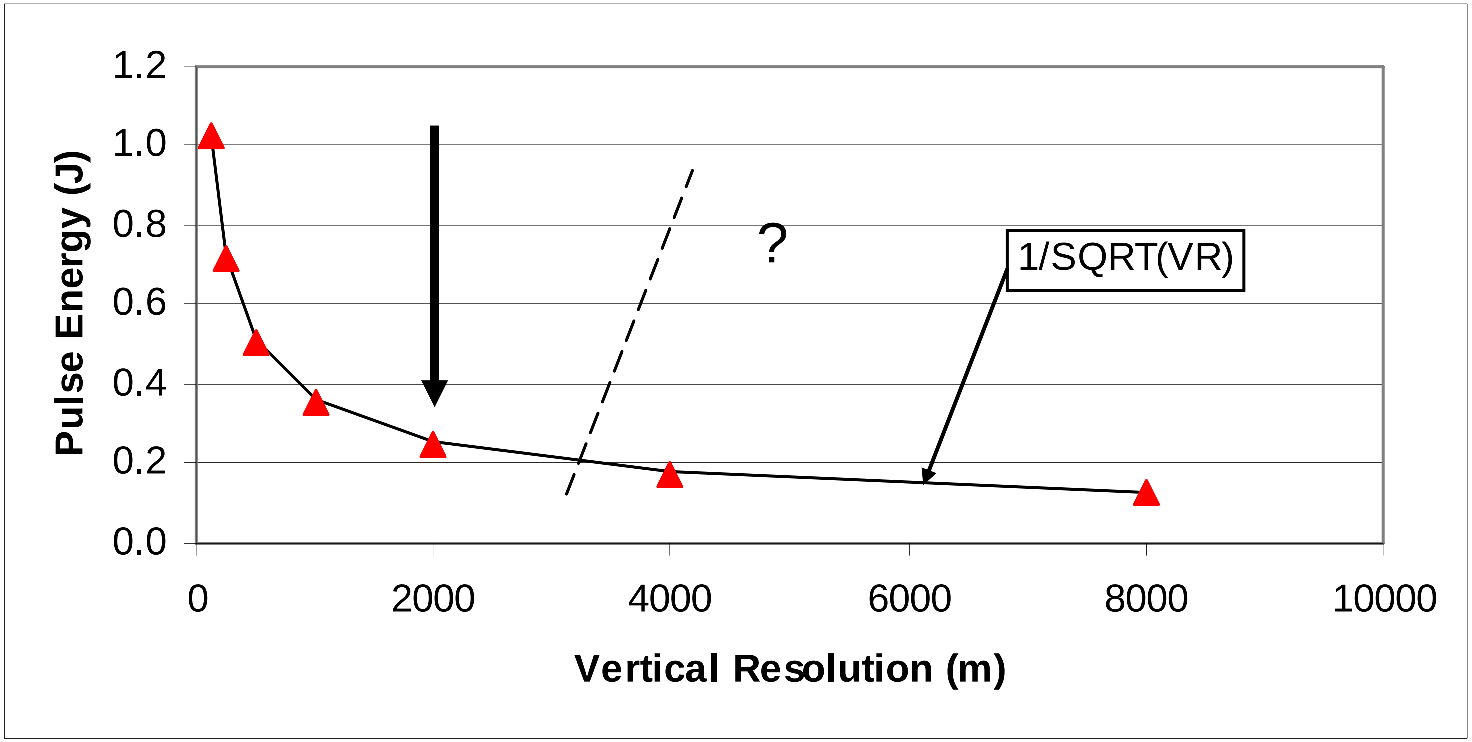


? = Outside the parameter limits of the underlying theory

$$\Rightarrow Is\ pulse\ energy \propto 1/\sqrt{vertical\ \ resolution}\ ?$$

Vertical Resolution vs. Pulse Energy

Yes

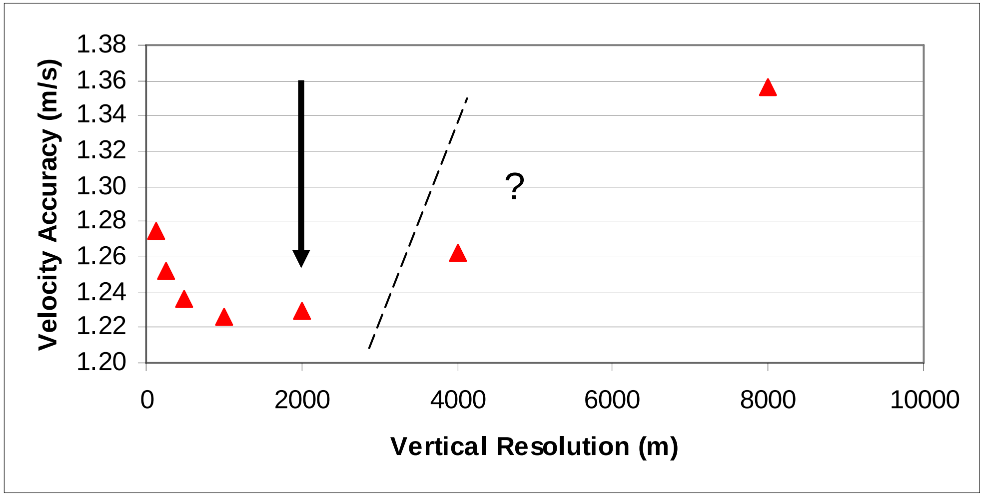


? = Outside the parameter limits of the underlying theory

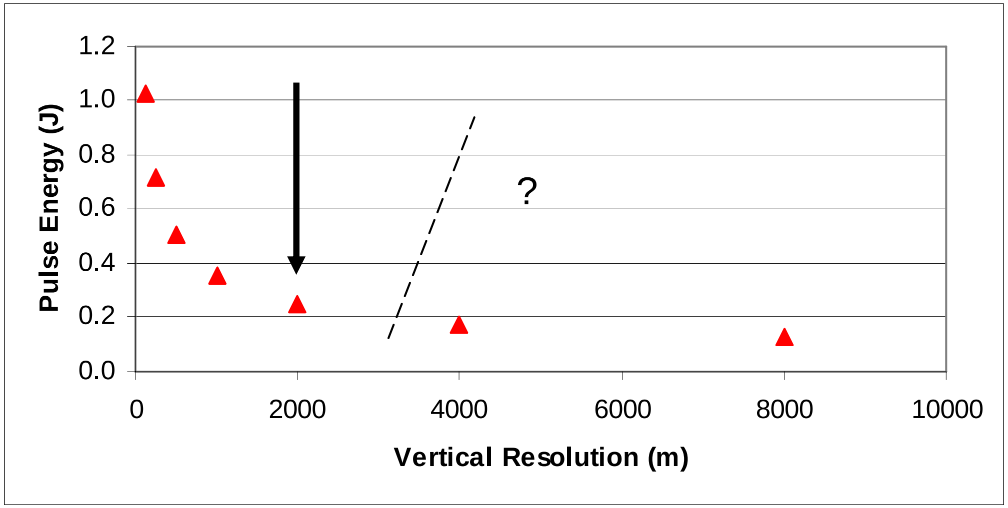
What is happening to the velocity accuracy? ⇒

Vertical Resolution vs. Velocity Accuracy

Velocity Accuracy



Pulse Energy



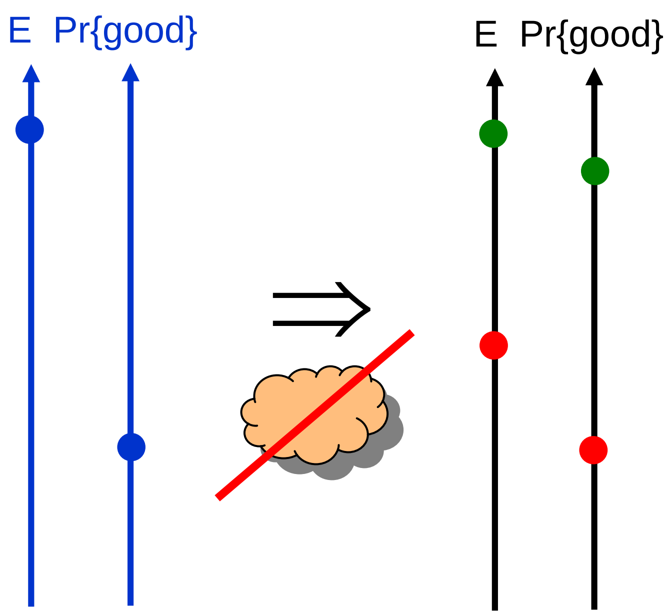
? = Outside the parameter limits of the underlying theory

Effect of Two GTWS Cloud Layers

- Cloud layer at 9-10 km = 0.14 km^{-1}
- Cloud layer at 2-3 km completely blocks 50% of the lidar shots
- Consider wind measurement at 1 km altitude
- Enhanced aerosol levels, $\beta = 2.5 \times 10^{-7}$ $m^{-1}sr^{-1}$

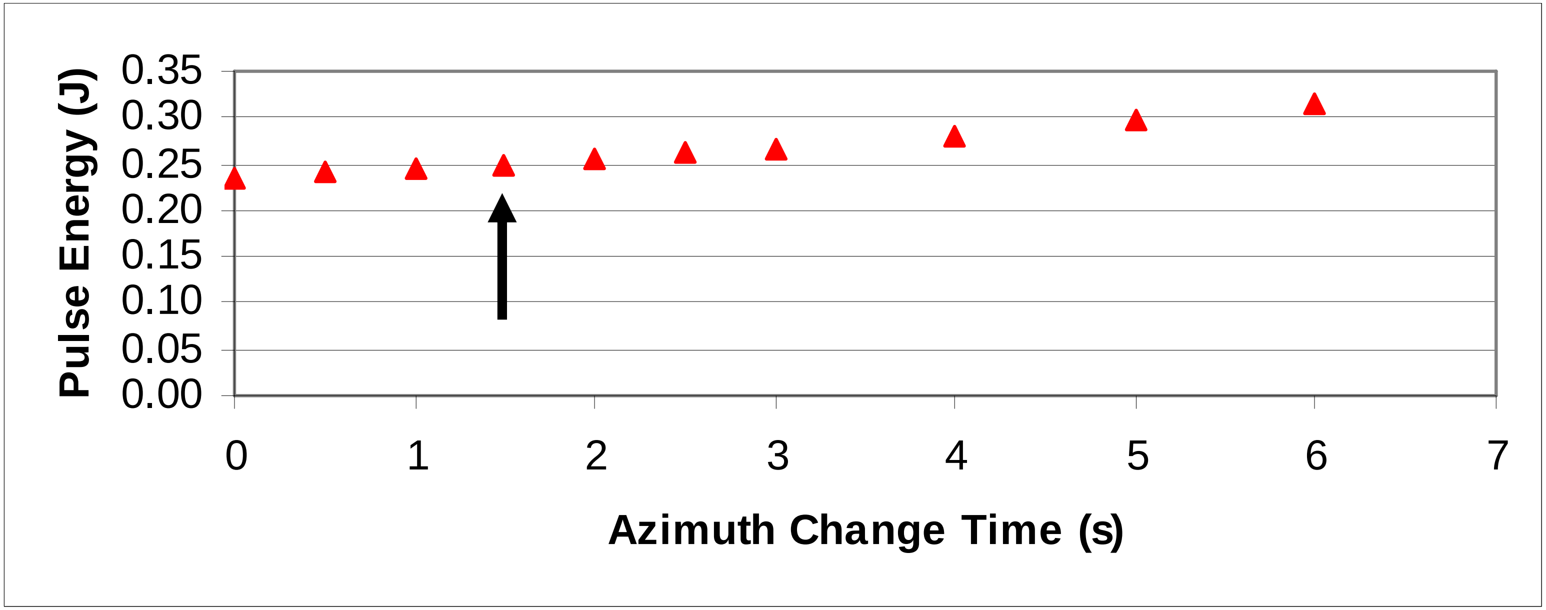
- With clouds included:
  - E = 30 mJ, Pr{good} = 0.33, Total wind accuracy = 1.84 m/s

- Without clouds included:
  - Either E = 30 mJ, Pr{good} = 0.8, Total wind accuracy = 1.83 m/s
  - Or E = 15 mJ, Pr{good} = 0.33, Total wind accuracy = 1.83 m/s

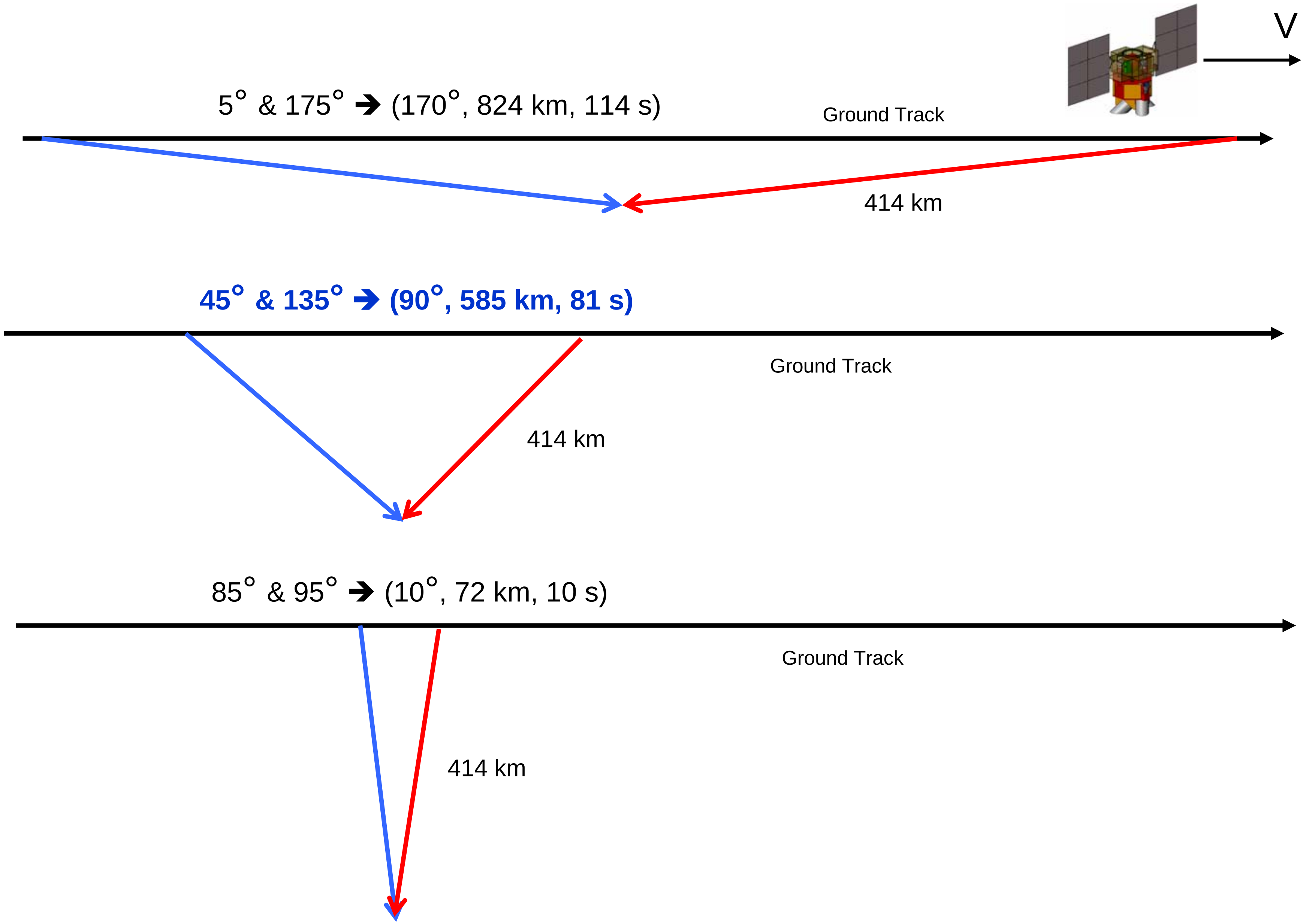


Azimuth Change Time vs. Pulse Energy

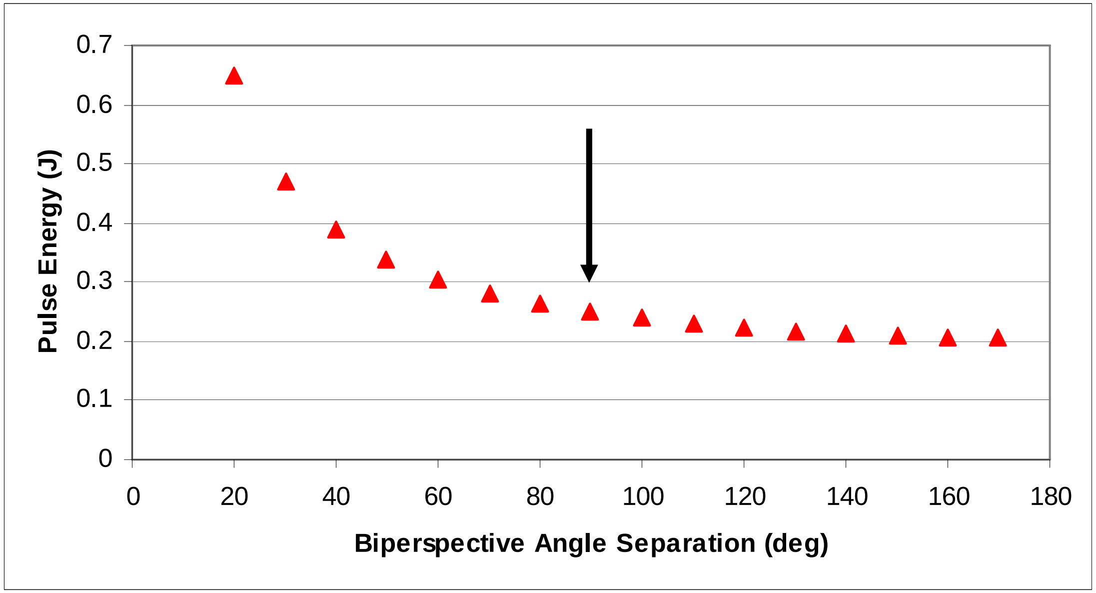
- Hold shot accumulation time + azimuth change time = 13.5 s
- Hold Pr{good} <u>and</u> velocity accuracy constant

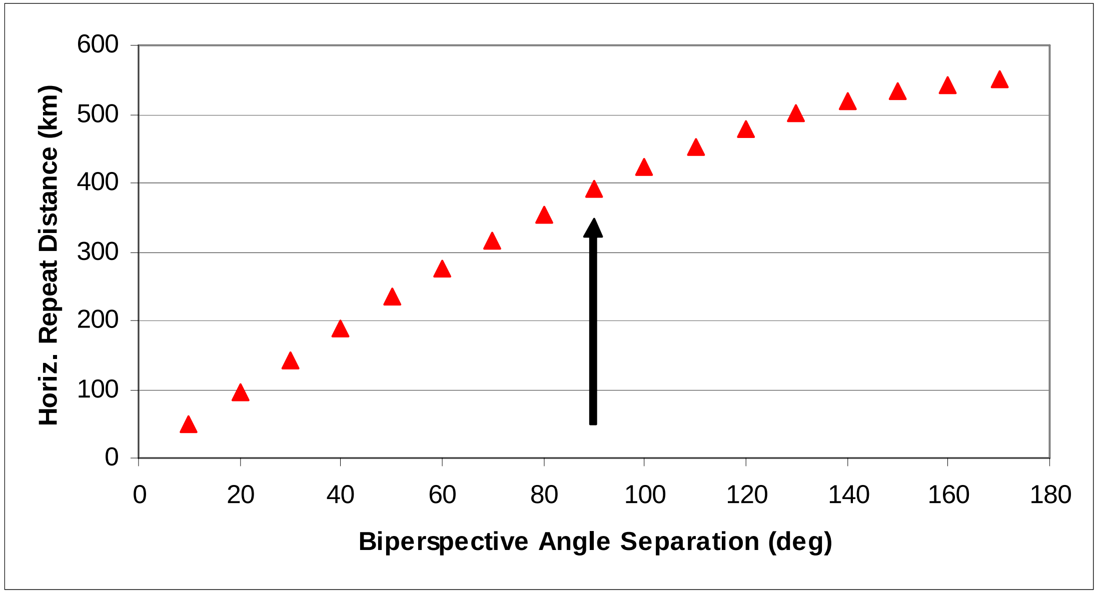


Biperspective Angle Separation Affects Fore/Aft Overlay Time Delay and therefore Shot Accumulation Time



Biperspective Angle Separation vs. Pulse Energy & Repeat Distance

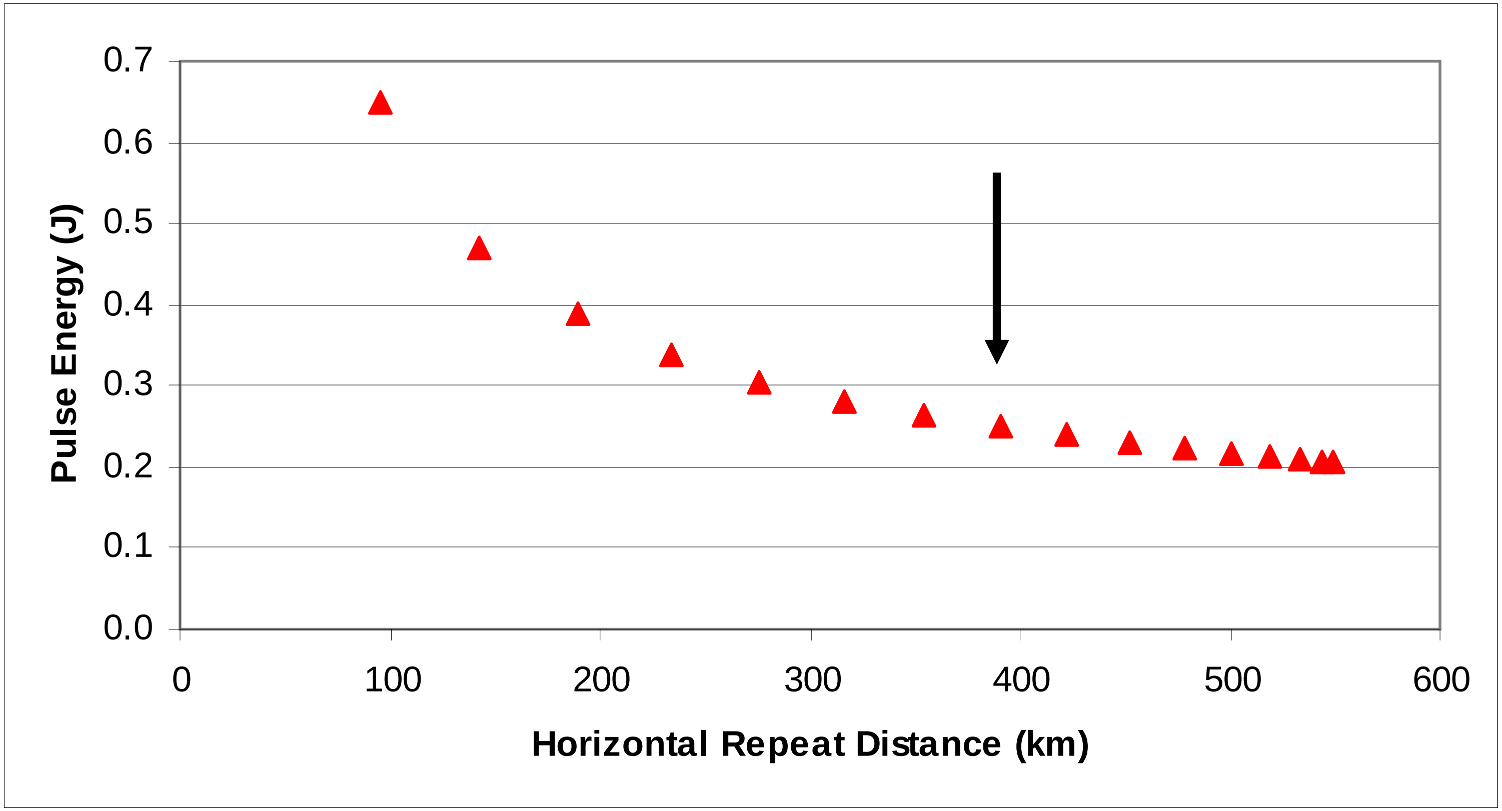




- Hold Pr{good} <u>and</u> velocity accuracy constant
- Hold PRF = 5 Hz
- Hold azimuth change time = 1.5 s
- Sampling error changes not included

Horizontal Repeat Distance vs. Pulse Energy

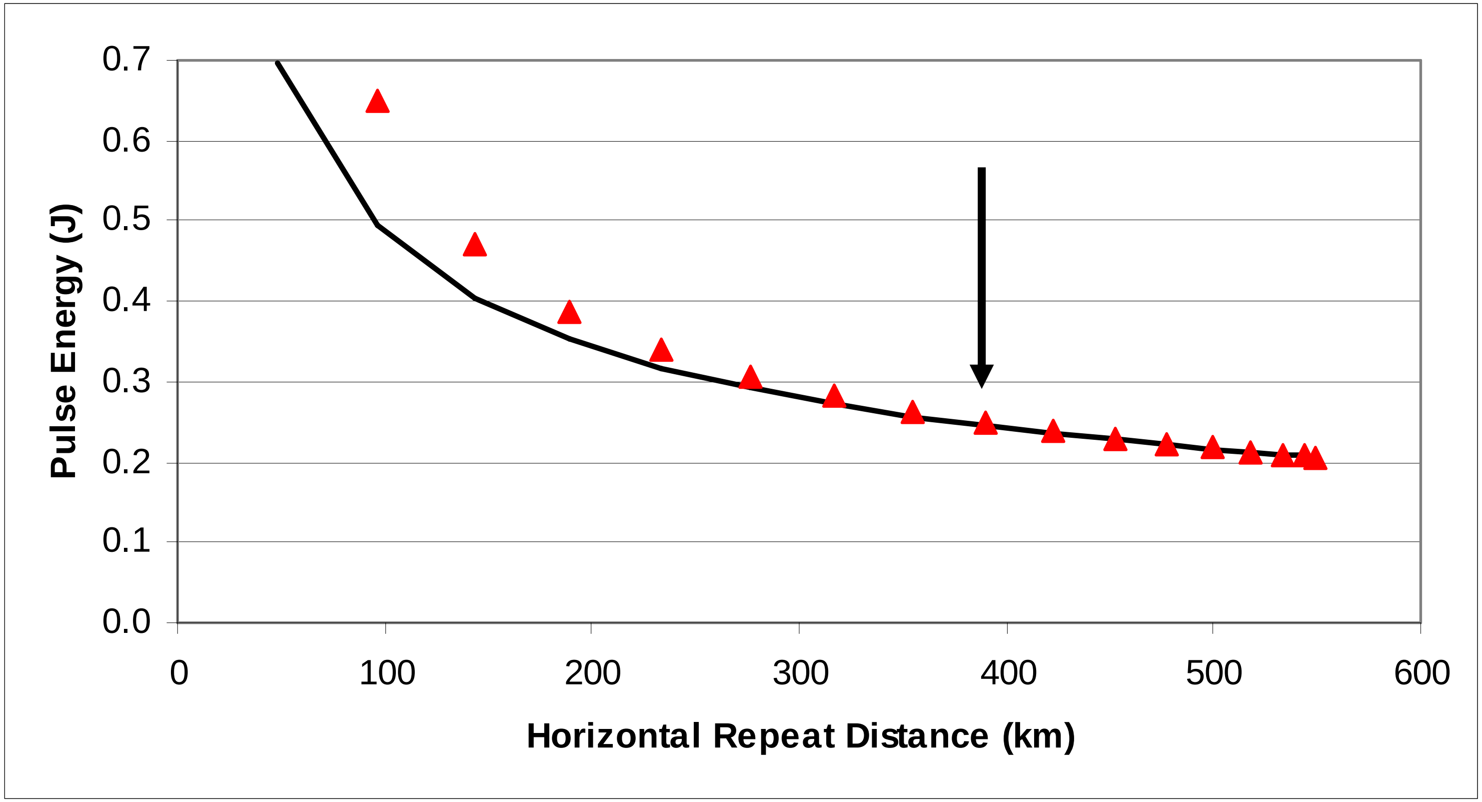
- Combine two plots on previous slide
- Sampling error changes not included



$\Rightarrow$ *Is pulse energy* $\propto 1/\sqrt{\text{horizontal repeat distance}}$?

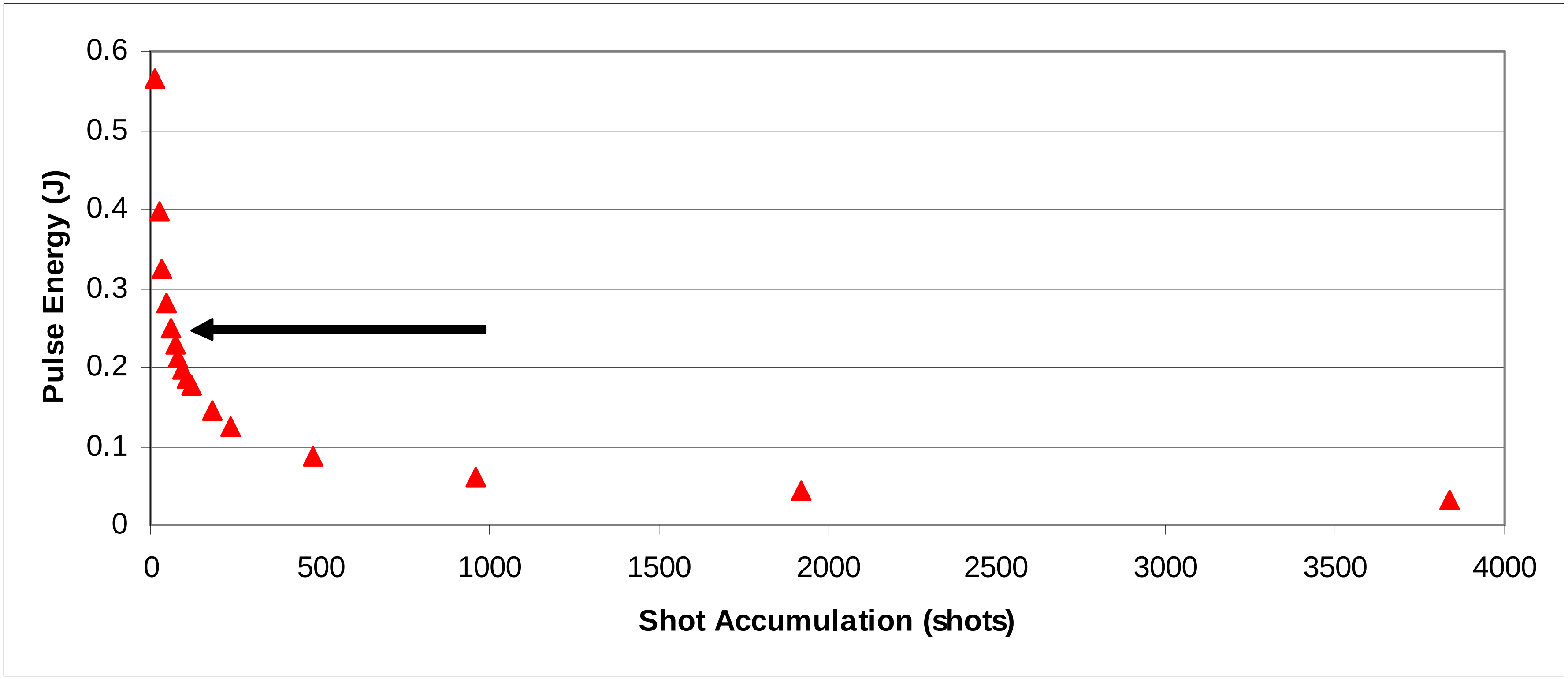
Horizontal Repeat Distance vs. Pulse Energy

Fit fails as HR distance gets small due to azimuth change time effect



Shot Accumulation vs. Pulse Energy

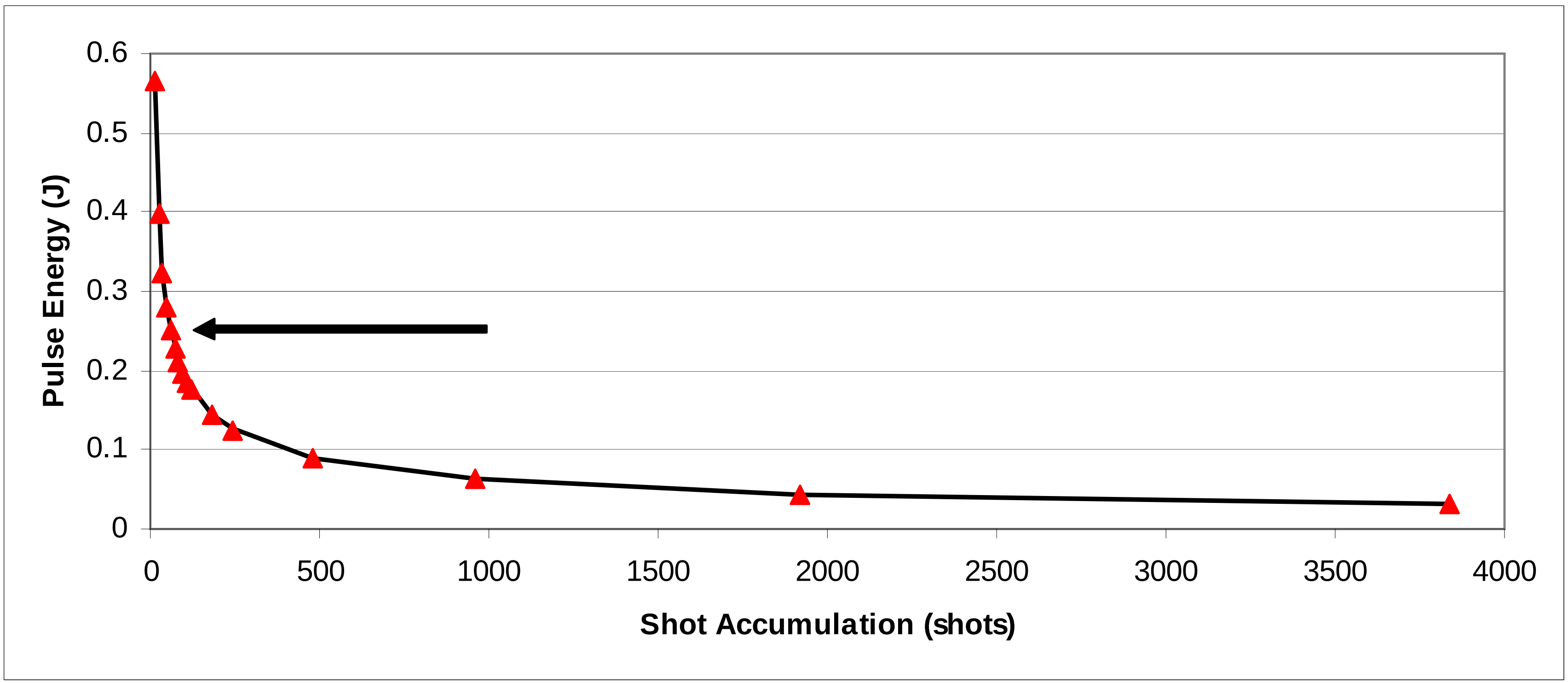
- Hold Pr{good} = 0.5
- Sampling error changes only included if PRF is varied, not if accumulation time is varied



$\Rightarrow$ *Is pulse energy* $\propto 1/\sqrt{\text{shot accumulation}}$?

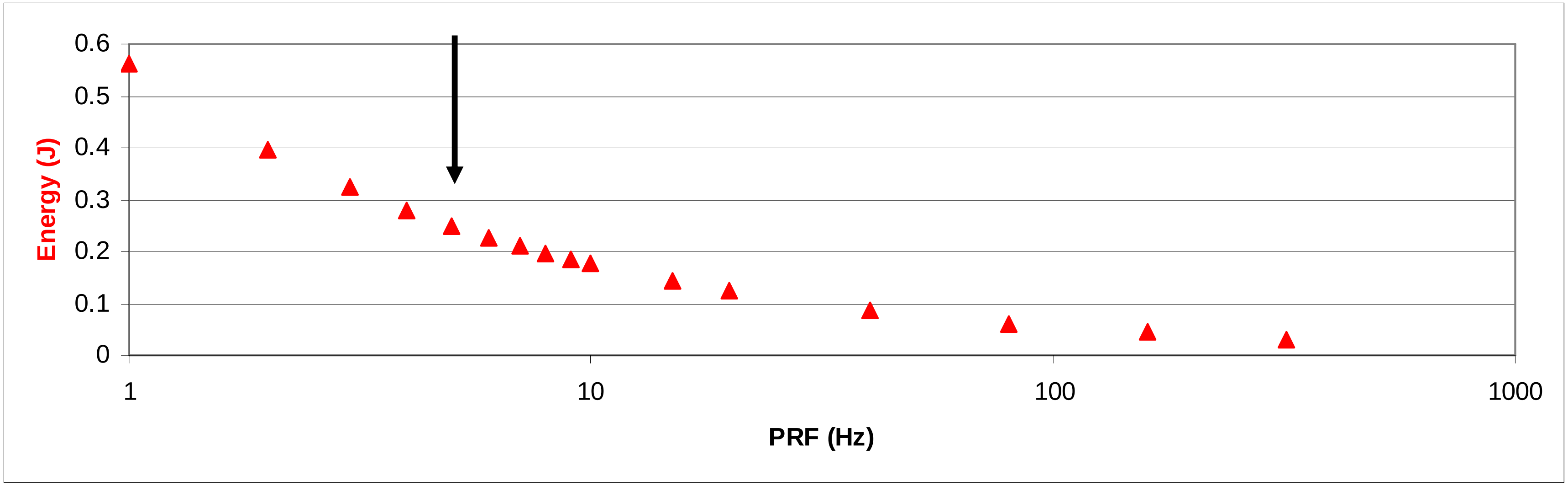
Shot Accumulation vs. Pulse Energy

Yes



PRF vs. Pulse Energy

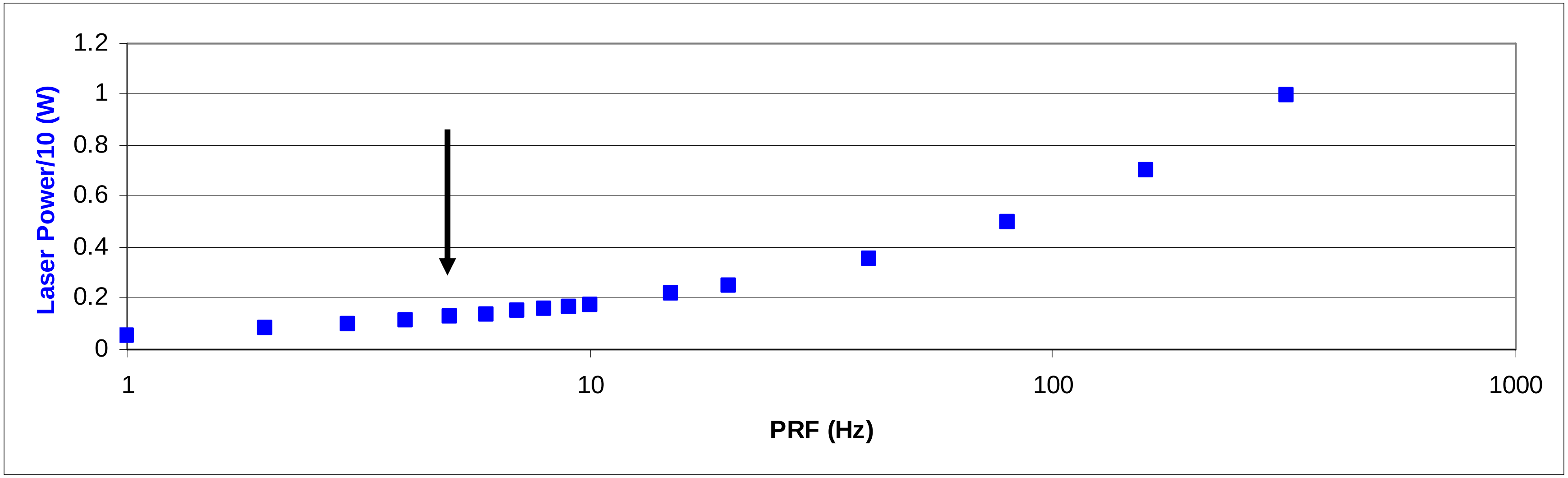
- Hold Pr{good} = 0.5



➔ Since lower energy lasers are easier, go to higher PRF? Not so fast …

PRF vs. Laser Power

- Hold Pr{good} = 0.5
- Laser Power = Energy x PRF



➔ Since lower average power lasers are easier, go to lower PRF? Not so fast …

LDA Lifetime Theory

$$Lifetime \propto (T_U - T_L)^{-N} e^{\frac{E_a}{k_B T_U}}$$

PRELIMINARY LRRP RESULTS PER F. AMZAJERDIAN

T_U = LDA temperature cycle upper limit

T_L = LDA temperature cycle lower limit

$N \sim 4$

$E_a \sim 0.9$ eV

$T_U(P) \sim 0.27P + 26.3$ °C

$T_U - T_L \sim 0.21P + 1.14$ °C

P = LDA power

P = (E + 3/7) x 70

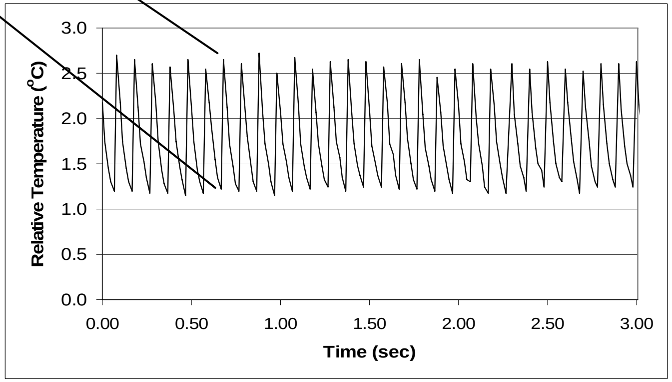
T_U and T_L independent of PRF for 3 < PRF < 20

Equations good up to about 20 Hz PRF

$k_B = 1.3806503 \times 10^{-23}$ m²kg/(s² °K)

°K = °C + 273.15

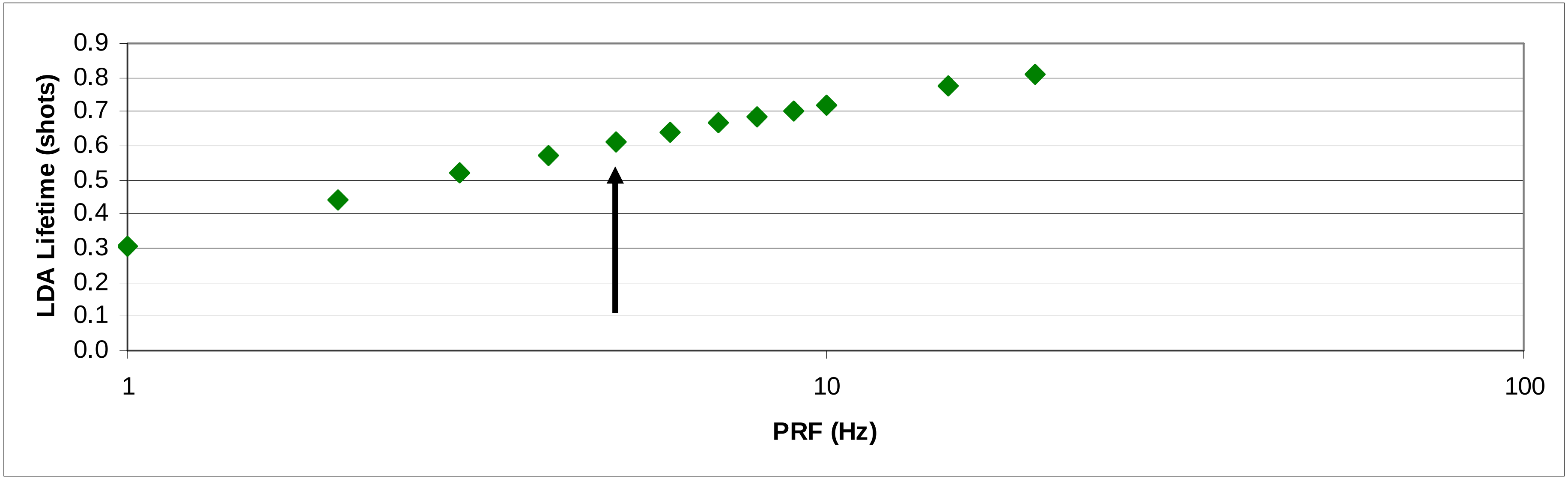
1 J = $6.24150974 \times 10^{18}$ eV



PRF vs. LDA Lifetime

PRELIMINARY FOR TRADE CONCEPT ONLY

- Hold Pr{good} = 0.5
- Assume LDA lifetime reflects laser lifetime

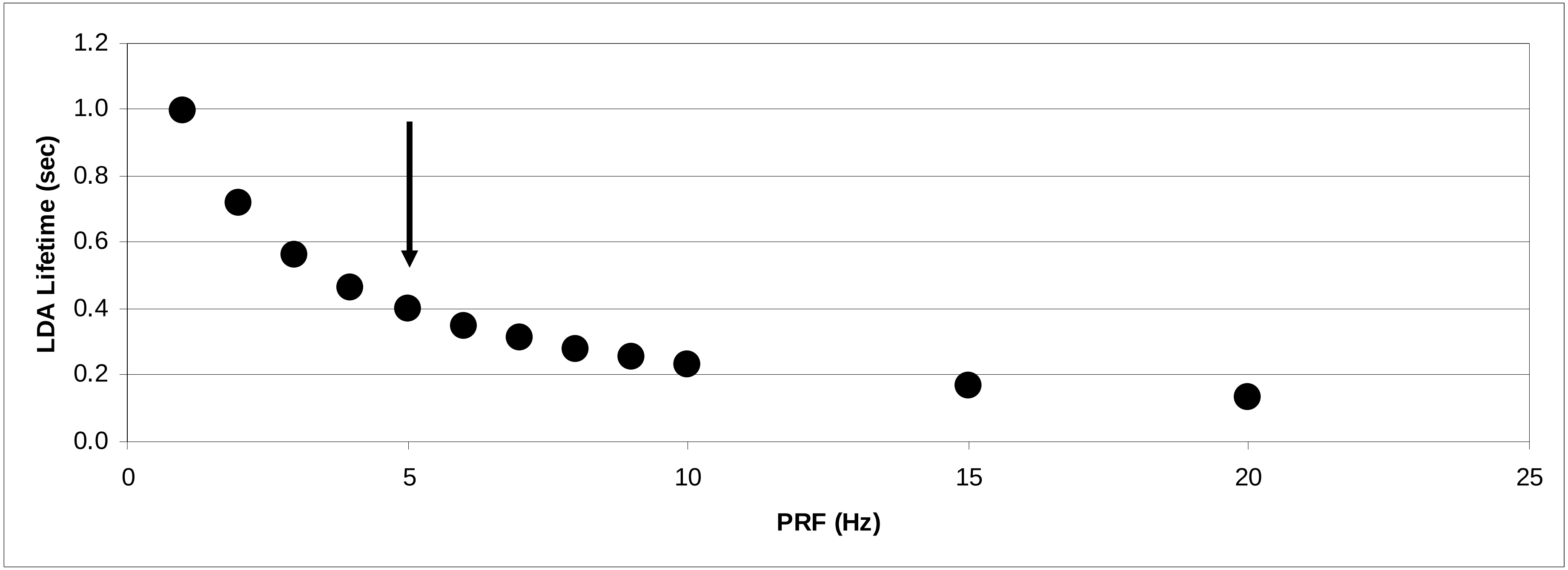


➔ Since higher lifetime is desired, go to higher PRF? Not so fast, …

PRF vs. LDA Lifetime

PRELIMINARY
FOR TRADE
CONCEPT ONLY

- Hold Pr{good} = 0.5
- Lifetime in seconds more important than lifetime in shots
  (seconds = shots/PRF)



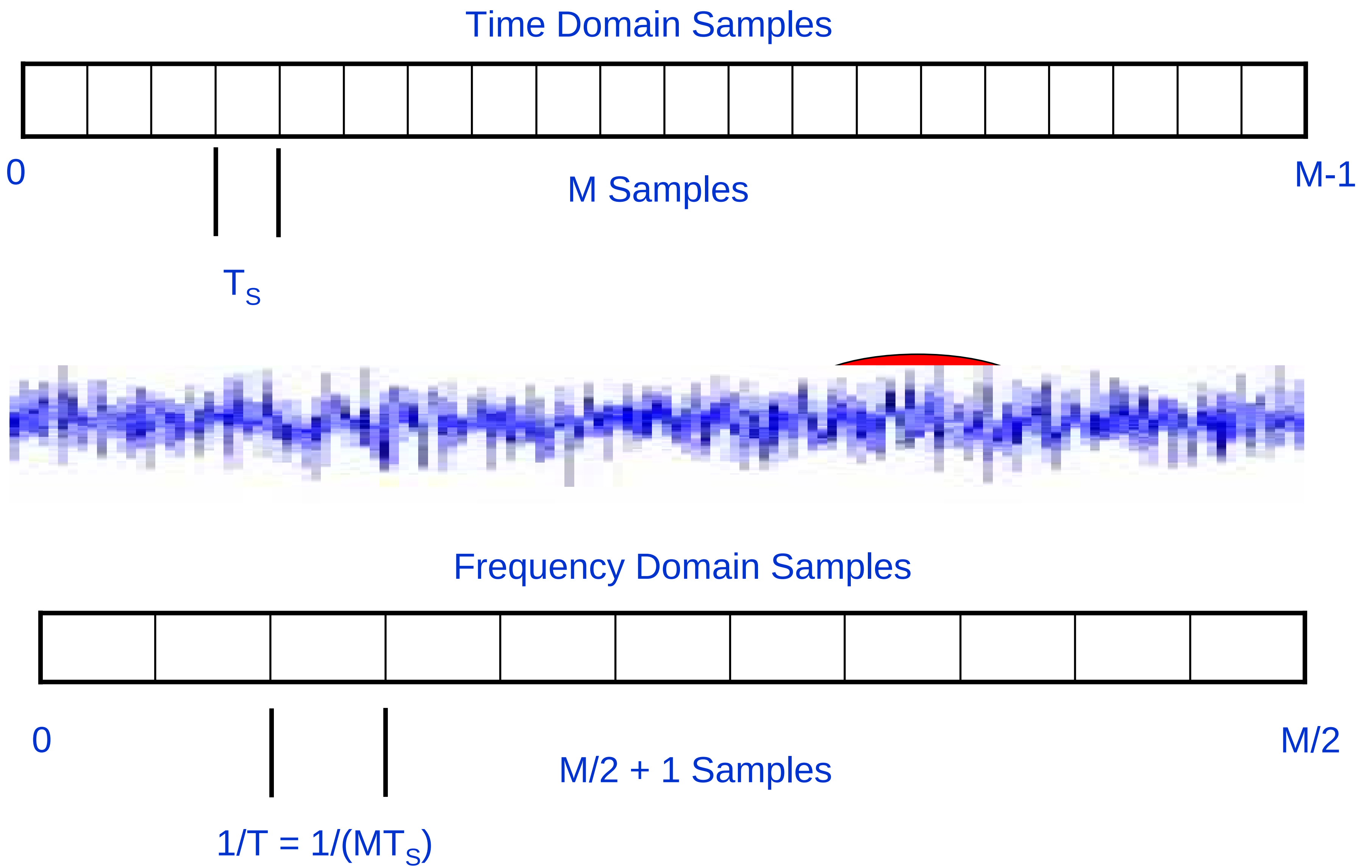
➔ Since higher lifetime is desired, go to lower PRF? __________

Summary and Conclusions

- LaRC computer simulation of global wind profiling coherent-detection Doppler lidar uses latest published theory
- Also includes detailed, bottoms-up section to calculate Lidar System Efficiency (LSE)
- SWA simulation much more sophisticated in modeling atmosphere and its variability
- LaRC simulation permits parametric trade studies with choice of parameters held constant
- If simulation trade results could be verified by experiment, space mission design parameters could be further optimized, yielding more science product and/or less cost

Back Up Slides

DFT


Time Domain Samples
0
M Samples
M-1
T_S
Frequency Domain Samples
0
M/2 + 1 Samples
M/2
$1/T = 1/(MT_S)$

Use of Frehlich's Theory

$\underline{\lambda}, \underline{V_{SEARCH}} \Rightarrow T_S$ $\qquad$ $T_S, \underline{\Delta p} \Rightarrow M$

$\underline{\text{Pulse duration } \tau}, \underline{\text{XMTR - LO } \Delta\text{f K.E}}, \underline{\text{wind turb.}}, \underline{\text{vert. wind shear}} \Rightarrow \text{w}_{\text{EFF}}$

$$T_S, M, w_{EFF} \Rightarrow \Omega$$

Select $\underline{b_{THR}}$ = Maximum permitted value

$b_{THR}, M, \Omega, \underline{N} \Rightarrow \Phi_{THR,1}$ (Minimum permitted for 1 shot)

$b_{THR}, M, \Omega, N, w_{EFF} \Rightarrow$ g (RMS error of good wind estimates)

$\varphi_{THR,1}, M, T_S, \underline{Lidar\ Equation} \Rightarrow \beta_{THR}$

V_{SEARCH} = Full LOS velocity search bandwidth on last pass through data

Δp = range-gate length

τ = pulse duration

N = accumulated shots per wind estimate

b = probability of a bad wind estimate

Ω = independent samples per range gate

T – range-gate time (signal collection time)

w = signal spectrum width

M = complex samples per range gate

T_S = complex data sampling interval

Φ = coherent photoelectrons per range gate

Use of Frehlich's Theory

$$T_S = \frac{\lambda}{2V_{SEARCH}} \qquad T = \frac{2\Delta p}{c}$$

$$M = \frac{T}{T_S} = \frac{2\Delta p}{cT_S} = \frac{4\Delta p V_{SEARCH}}{c\lambda}$$

$$\Omega = \frac{2w_{VEFF}MT_S}{\lambda} = \frac{4w_{VEFF}\Delta p}{c\lambda} \qquad \frac{\Omega}{M} = \frac{w_{VEFF}}{V_{SEARCH}} < 0.2$$

V_{SEARCH} = Full LOS velocity search bandwidth on last pass through data

Δp = range-gate length

τ = pulse duration

N = accumulated shots per wind estimate

b = probability of a bad wind estimate

Ω = independent samples per range gate

T – range-gate time (signal collection time)

w = signal spectrum width

M = complex samples per range gate

T_S = complex data sampling interval

Φ = coherent photoelectrons per range gate

Frehlich's Theory Dependencies

	$\Phi_{1,THR}$ (coh e^{-}/range-gate)	g (m/s)	β_{THR} (m^{-1} sr^{-1})	Notes
λ (m)	X	X	X	Wavelength
V_{SEARCH} (m/s)	X	X	X	Search Bandwidth
Δp (m)	X	X	X	Range Gate Length
τ_p (s)	X	X	X	Pulse Duration
Δf K.E. (Hz)	X	X	X	XMTR-LO freq. diff.
Wind Turb. (m/s)	X	X	X	
Wind Shear (m/s/km)	X	X	X	
b_{THR}	X	X	X	Prob{bad wind estimate}
N_{ACCUM} (-)	X	X	X	Shot Accumulation per wind estimate
Lidar Equation			X	Pulse Energy, Range, Rec'r Area, Extinction, Efficiency, λ, V_{SEARCH}, Δp