# A Space-Based Coherent Doppler Wind Lidar Point Design For The NASA/NOAA Draft Science And Operational Data Requirements Of 16 October 2001

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# Acknowledgements

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# NASA/NOAA Draft Data Requirements 10/16/01

Point Design (→ Threshold)

| | Threshold | Objective |
|---|---|---|
| **Depth of regard** (km) | 0- 20 | 0-30 |
| **Vertical TSV resolution** (km)<br>Top of DOR to tropopause<br>Tropopause to boundary layer top<br>Within boundary layer | <br>Not required<br>1<br>.5 | <br>2<br>.5<br>.25 |
| **Height assignment accuracy** (km) | .1 | .1 |
| **Horizontal TSV dimension** (km)<br>(maximum for averaging) | 100 | 25 |
| **Horizontal location accuracy** (km) | .5 | .5 |
| **Horizontal resolution** (km)<br>(distance between TSVs) | 350 | 100 |
| **Minimum X-track regard** (km)<br>(# in ( ) is # of TSVs) | ±400 (4) | ±625 (12) |
| **Number LOS perspectives in TSV**<br>(angular separation > 30 and < 150) | 2 | 2 |
| **Accuracy($1\sigma$) of LOSH** (m/s)<br>Above boundary layer<br>Within boundary layer<br>(number in ( ) is $\sigma_s$ within TSV) | <br>3(1.2)<br>3(1.2) | <br>2(1.4)<br>1(1) |
| **Horizontal component bias** (m/s) | .1 | .05 |
| **Maximum horizontal speed** (m/s)<br>Above boundary layer<br>Within boundary layer | <br>75<br>50 | <br>100<br>50 |
| **Temporal resolution** (hours)<br>(revisit period) | 12 | 6 |
| **Data product latency** (hours) | 2.75 | 2.75 |



http://nais.msfc.nasa.gov/cgi-bin/EPS/synopsis.cgi?acqid=99220

# CDWL POINT DESIGN ASSUMPTIONS - 1

- 400 km orbit
- 45 deg. nadir angle (conical surface of regard)
- 8 scanner azimuth settings
- 4 vector wind C-T distances of ±150 and ±350 km
  - 150 km:
    - Dual perspective angle projected to horiz. = 137°
    - 100 km TSV extends from 100 to 200 km
  - 350 km:
    - Dual perspective angle projected to horiz. = 64°
    - 100 km TSV extends from 300 to 400 km

# CDWL POINT DESIGN ASSUMPTIONS - 2

- 2.0518-micron CDWL
- 12 Hz transmitter laser pulse repetition frequency (PRF)
- 180 ns pulse duration (FWHM)
- Single pulselet/pulse
- *See Results* Pulse energy

- 0.75-m receiver mirror optical diameter
- 20 m/s full LOS processing velocity search space, last pass through data, NOT capture BW (26.626 m/s in horizontal), $B_{VS}$

# CDWL POINT DESIGN ASSUMPTIONS - 3

- 12% Lidar System Efficiency (SNR after removing range squared, pulse energy, aperture area, atmospheric extinction, aerosol backscatter coefficient, constant c/2)
- 60 lidar shots accumulated (attempted) per LOS measurement over 35.5 km line parallel to ground track (4.9 sec./LOS, 1.1 sec. to change scanner)
- 3 dB misalignment loss (requires 2 $\mu$rad = 1$\sigma$ budgeted misalignment angle outside lidar, XMTR vs. delayed RECR directions, half allocated to lidar/LSE, half to spacecraft)

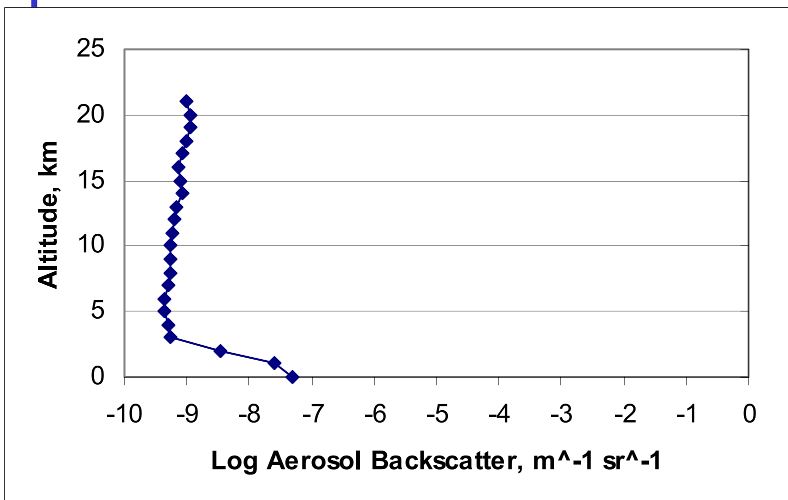
# CDWL POINT DESIGN ASSUMPTIONS - 4

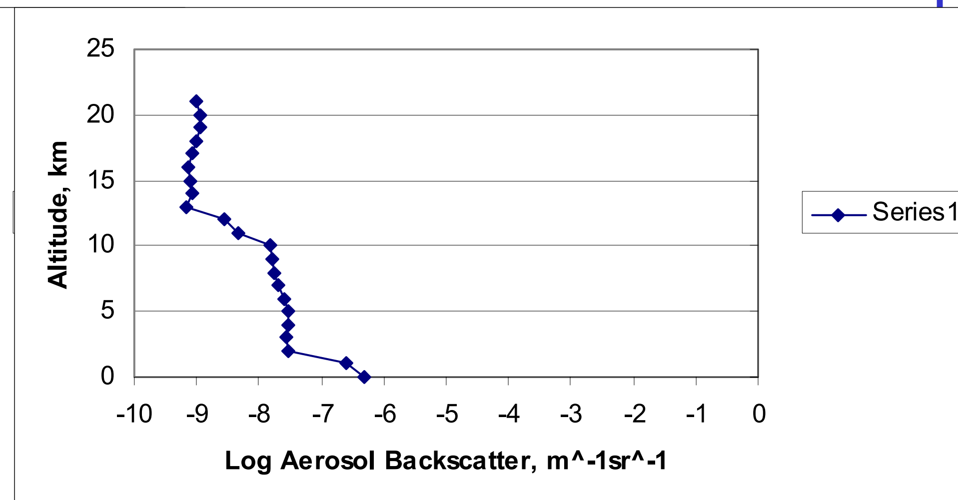
- “GTWS 10/16/01” provided 2.0610 micron background and enhanced aerosol backscatter profiles
- Earth is 75% background (low $\beta$) aerosol mode and 25% enhanced aerosol mode
- “GTWS 10/16/01” provided 2.0610 micron atmospheric extinction profiles
- Two “GTWS 10/16/01” provided cloud layers:
    - 9-10 km cloud layer has 2-way slant transmission = 0.65 = -1.8 dB
    - 2-3 km cloud layer blocks 50% of the lidar shots; otherwise no effect

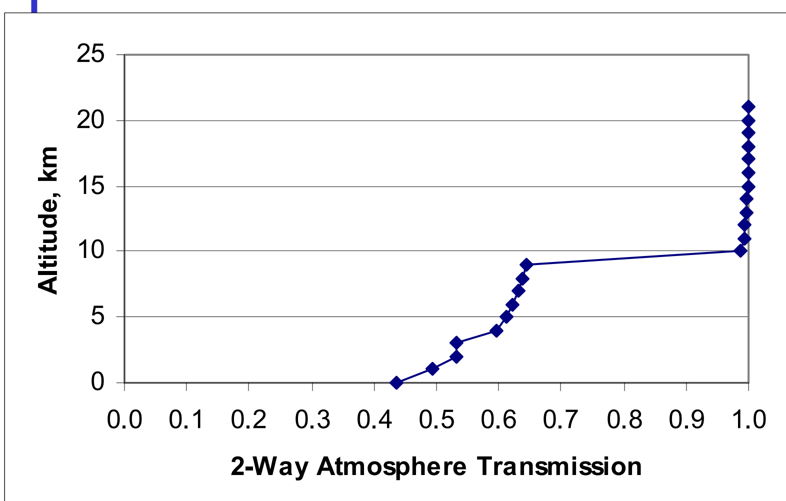
# Backscatter and Transmission

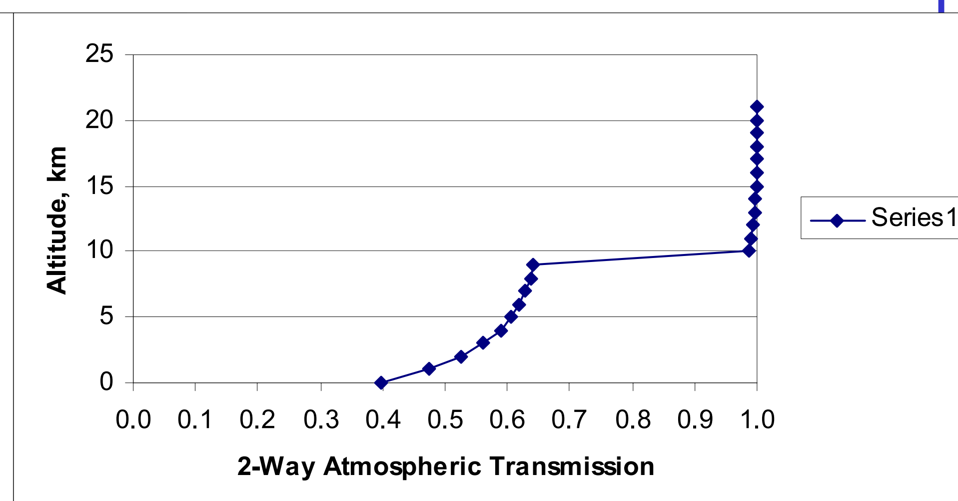
## Background

## Enhanced

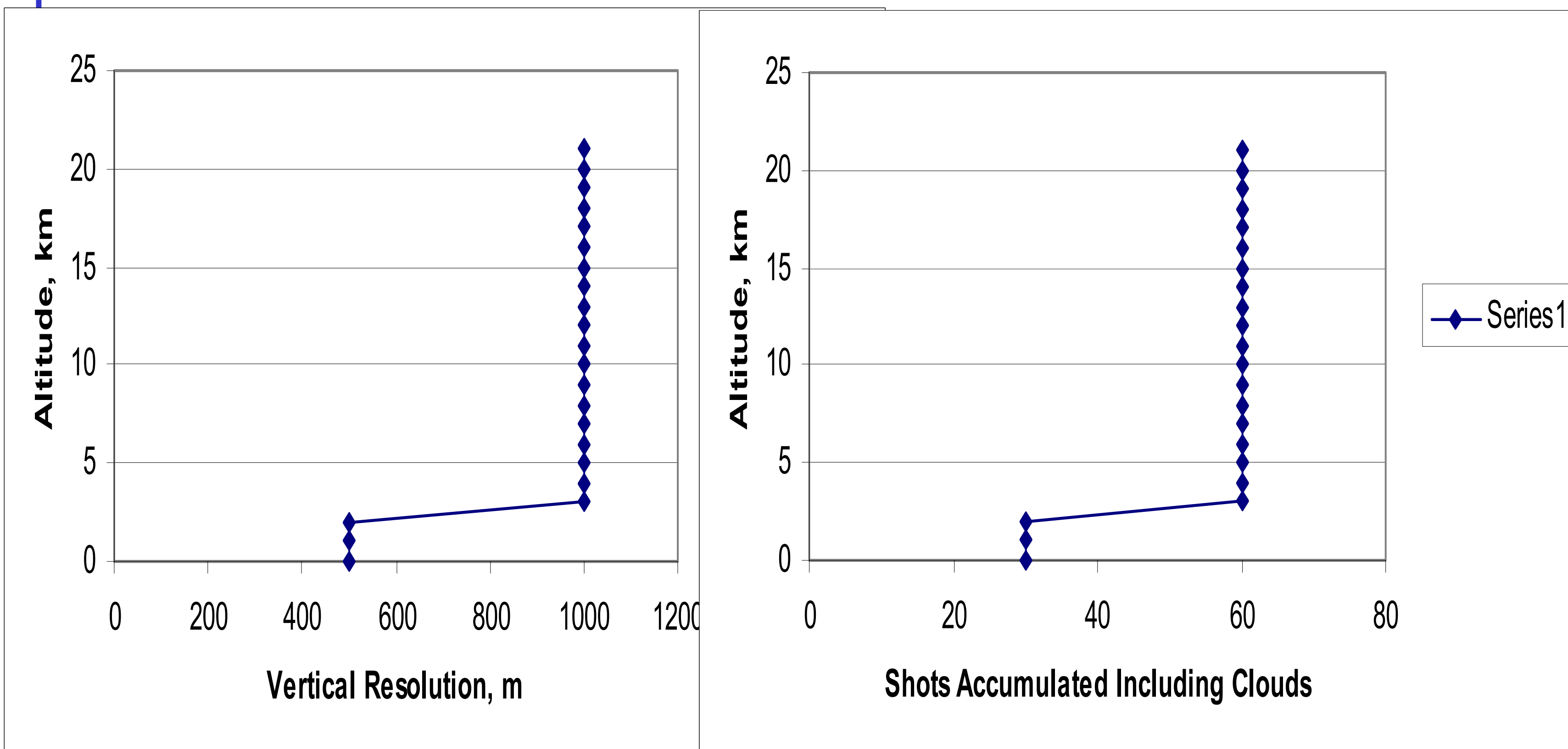


# Vertical Resolution and Shot Accumulation



# CDWL POINT DESIGN ASSUMPTIONS - 5

- Transmit Path Intensity Transmission
  - 0.955 Basic aperture
  - 0.99 T/R switch – pol. BS incl. polarization misal.
  - 0.99 T/R switch - quarter wave plate
  - 0.95 Telescope
  - 1 Scanner (No additional scanner)
  - 1 Pressure window (no PW)
  - 0.97 All other optics
  - 1 All obscurations (none)

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  - 0.863 Sub product

# CDWL POINT DESIGN ASSUMPTIONS - 6

Receiver Path Intensity Transmission

- 1 Pressure window (no PW)
- 1 Scanner (No additional scanner)
- 0.95 Telescope
- 0.99 T/R switch - quarter wave plate
- 0.9 T /R switch – pol. BS incl. pol. misal.
- 0.89 LO/signal beam splitter (BS)
- 0.97 All other optics
- 1 All obscurations (none)
- 1 Fibers, ports, & coupler (no fibers)

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- 0.731 Sub product

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- 0.630 T & R transmission sub product

# CDWL POINT DESIGN ASSUMPTIONS - 7

- SNR Reducing Aberration Factors

  - 0.95 Telescope, 2 passes
  - 0.95 Telescope, incorrect focus setting
  - 1 Scanner, 2 passes (no extra scanner)
  - 1 Pressure window, 2 passes (no PW)
  - 0.98 Other optics, some 1 pass, some 2 pass

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  - 0.884 Aberration sub product

# CDWL POINT DESIGN ASSUMPTIONS - 8

- SNR Reducing Detection Terms

  - 0.95 Laser beam spatial quality
  - 1 Detector truncation
  - 0.42 Mixing efficiency
  - 0.98 XMTR/RECR polarization mismatch
  - 0.8 Detector quantum efficiency at IF frequency
  - 0.97 Detector nonlinearity factor
  - 0.97 Nondominating shot noise factor

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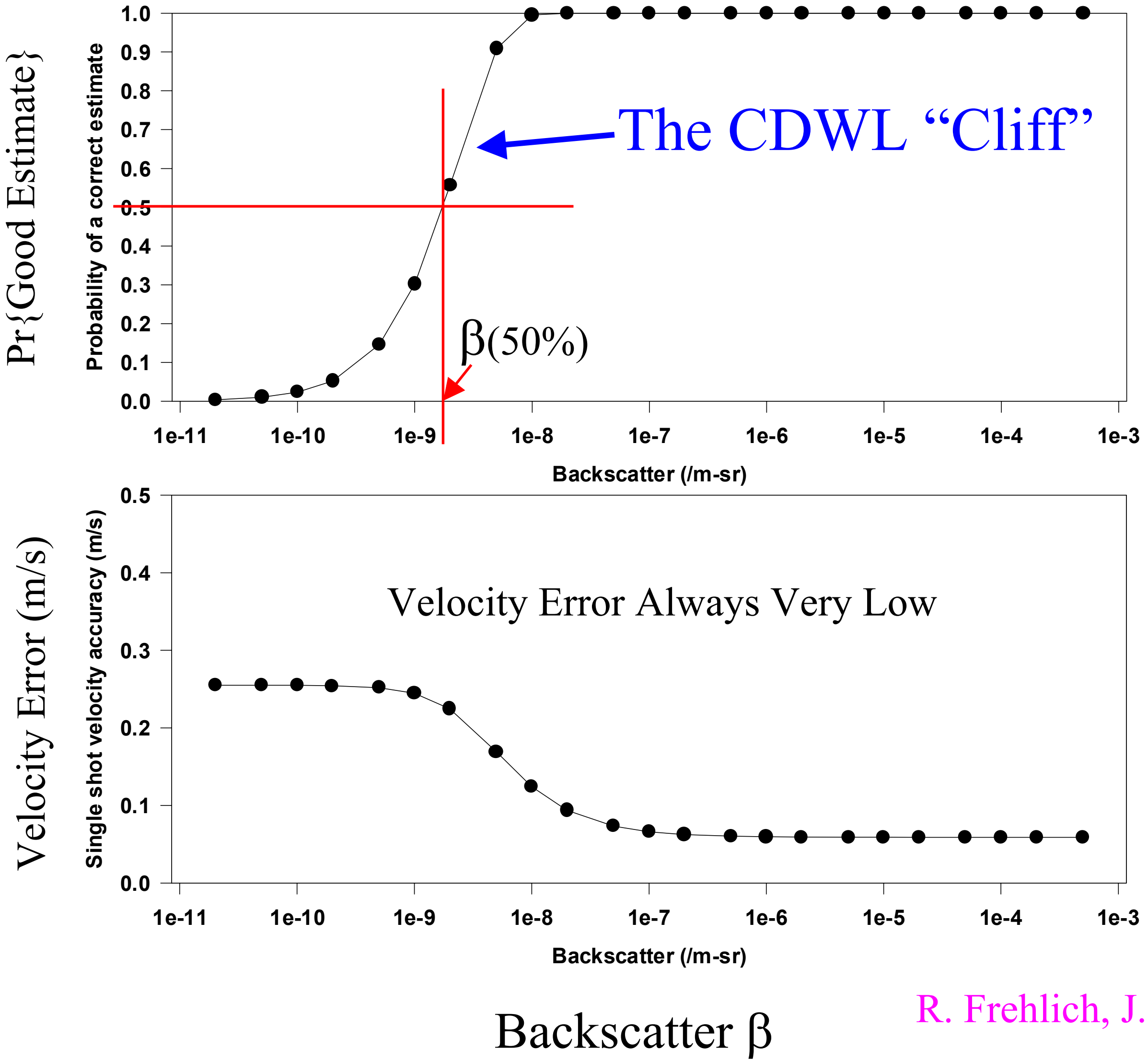
  - 0.294 Detection sub product

# CDWL POINT DESIGN ASSUMPTIONS - 9

- 0.5 Transmitter/receiver angle misalignment factor (2.053 μrad total 1σ misalignment angle outside lidar, 4 ms) (Assign half to lidar, half to spacecraft, 1.45 μrad each)

| | | |
|---|---|---|
| X | 0.707 | Lidar portion of T/R angle misalignment factor $\eta_{MIS,L}$ |
| X | 0.630 | T/R intensity transmission factor |
| X | 0.884 | Aberration sub product |
| X | 0.294 | Detection sub product |
| • | 0.116 | Lidar System Efficiency (LSE) |
| • | 0.707 | Spacecraft portion of T/R angle misalignment factor, $\eta_{MIS,S}$ |

# Example of coherent lidar velocity estimator performance




## 2 Figures Of Merit

Maximum and minimum values and shape of each will vary with lidar parameters. However 'S' shape and the relationship between the two curves are characteristic of all advanced coherent lidar velocity estimators.

Theory and experiment <u>agree</u> to within 5%.

R. Frehlich, J. Atmos. & Oceanic Tech. 14, 54 (1997).

# Wind Shear Dilemma

- Science requirements provide U wind magnitude value at each integer height in km
- Highest shear of 15 m/s/km at 8-9 & 10-11 km
- No statistics of wind shear magnitude & direction
- Highly unlikely that lidar shot is always aligned with horizontal wind

# Final Velocity Error Calculation

$\sigma_{gH} = \sigma_g/\sin(\Theta_{NT})$ Error std. dev. of good estimates projected to horizontal [m/s]

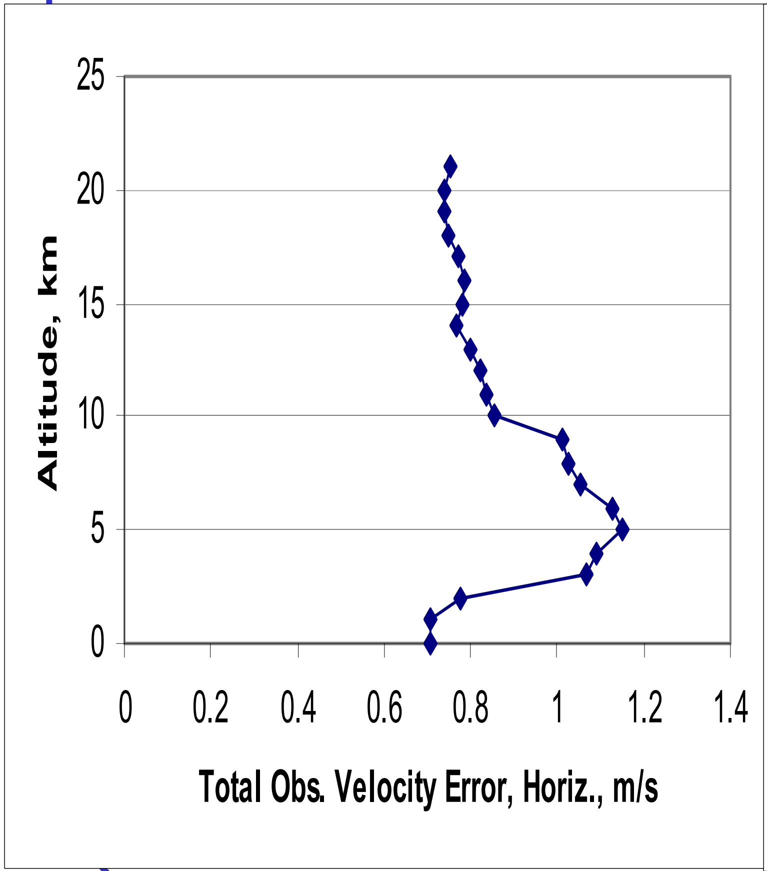
$\sigma_{gT} = \mathrm{SQRT}[\sigma^2_{gH} + \sigma^2_{NLH} + \sigma^2_{SA}]$ Total error

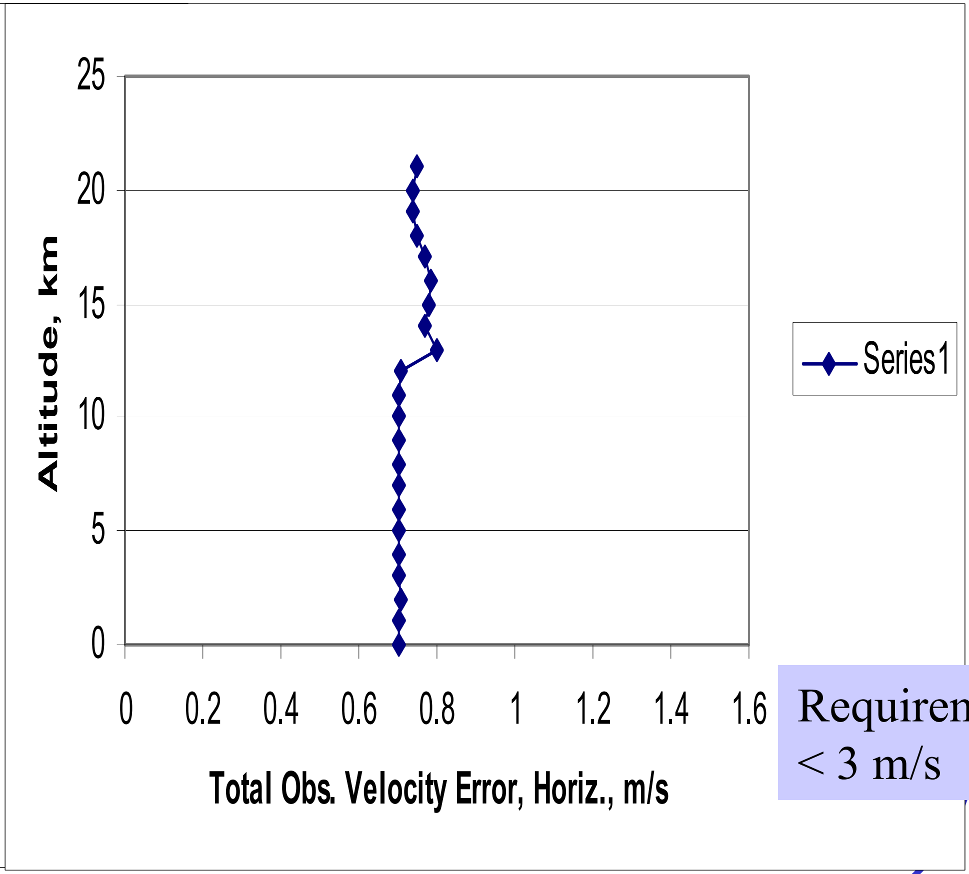
$\sigma_{NLH} = 0$ m/s Non-lidar, proj. to horiz.

$\sigma_{SA} = 0.7$ m/s Sampling error

# CDWL POINT DESIGN RESULTS - $\sigma_g$

Background, 50th 5.0 J Enhanced, 50th



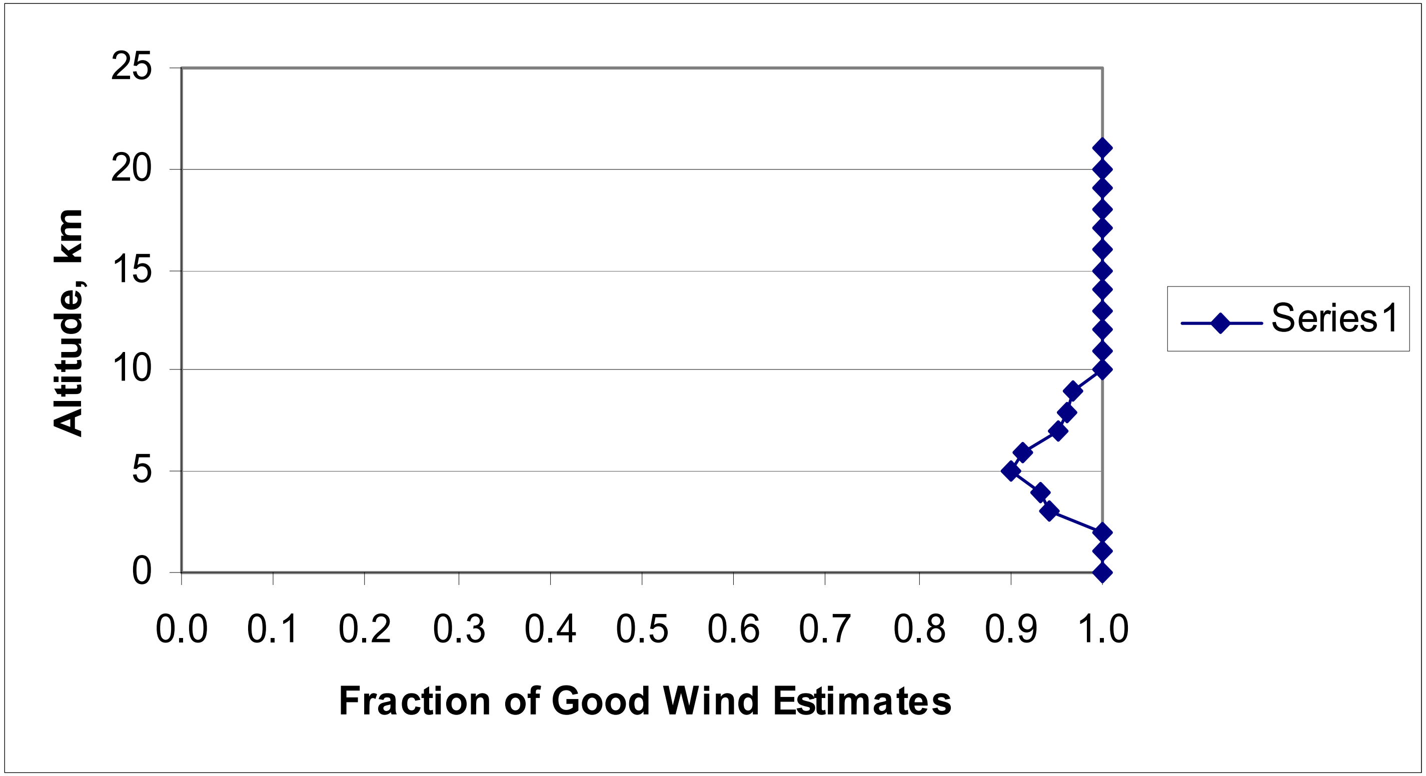




Requirement:
< 3 m/s

# CDWL POINT DESIGN RESULTS - g
## 5.0 J

Assume: 75% Background (50th); 25% Enhanced (50th)

Enhanced includes aerosols & clouds; most applicable below tropopause (8 – 19 km)



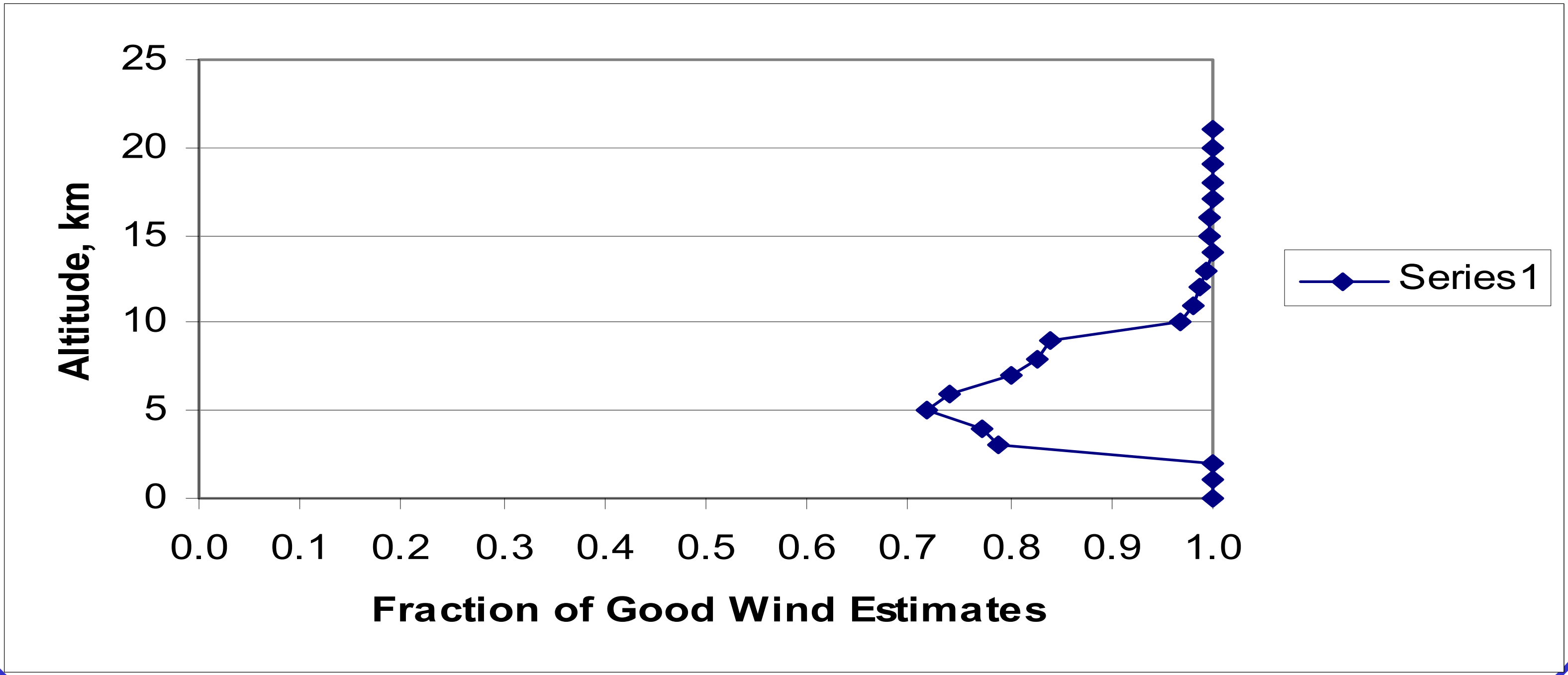
# However …

- Good performance from 10 – 20 km (relative to 5 km) due to provided background β curve increasing with altitude; needs confirmation

- Science Requirements:“A threshold fraction of 50% of all the wind observations made by an orbiting DWL must meet the standards set in the GTWS requirements table.”
- Even with g > 0.9, the CDWL misses the lowest β tail of the atmosphere because 0.9 x 0.5 = 0.45 is not > 0.5
- Therefore attempt to model other percentiles of β …

# CDWL POINT DESIGN RESULTS - g
## 4.9 J

Assume: 75% Background (70th); 25% Enhanced (70th)
Background x 0.66; Enhanced x 0.59
g > 0.72 because 0.70 x 0.72 = 0.504 > 0.5



# Summary Of Cases

| β model | β percentile | CDWL g | Altitudes Covered | Pulse Energy, J |
|---|---|---|---|---|
| **Combined** | 50% | 90% | 0-20 | 5.0 |
| **Combined** | 60% | 84% | 0-20 | 5.2 |
| **Combined** | 70% | 72% | 0-20 | 4.9 |
| **Combined** | 80% | 63% | 0-20 | 5.2 |
| **Combined** | 90% | 56% | 0-20 | 6.2 |
| | | | | |
| Background | 50% | 90% | 0-20 | 5.5 |
| **Combined** | 50% | 90% | 0-20 | 5.0 |
| Enhanced | 50% | 90% | 0-20 | 2.0 |
| Background | 90% | 56% | 0-20 | 8.1 |
| **Combined** | 90% | 56% | 0-20 | 6.2 |
| Enhanced | 90% | 56% | 0-20 | 1.1 |

Slightly misses science requirements

# Add 5 m/s/km Wind Shear

| β model | β percentile | CDWL g | Altitudes Covered | Pulse Energy, J |
|---|---|---|---|---|
| **Combined** | 50% | 90% | 0-20 | 5.5 |
| **Combined** | 60% | 84% | 0-20 | 5.7 |
| **Combined** | 70% | 72% | 0-20 | 5.2 |
| **Combined** | 80% | 63% | 0-20 | 5.3 |
| **Combined** | 90% | 56% | 0-20 | 6.3 |
| | | | | |
| Background | 50% | 90% | 0-20 | 6.1 |
| **Combined** | 50% | 90% | 0-20 | 5.5 |
| Enhanced | 50% | 90% | 0-20 | 2.2 |
| Background | 90% | 56% | 0-20 | 8.4 |
| **Combined** | 90% | 56% | 0-20 | 6.3 |
| Enhanced | 90% | 56% | 0-20 | 1.1 |

Need up to 10% more pulse energy

Slightly misses science requirements

# Reduced Vertical Coverage

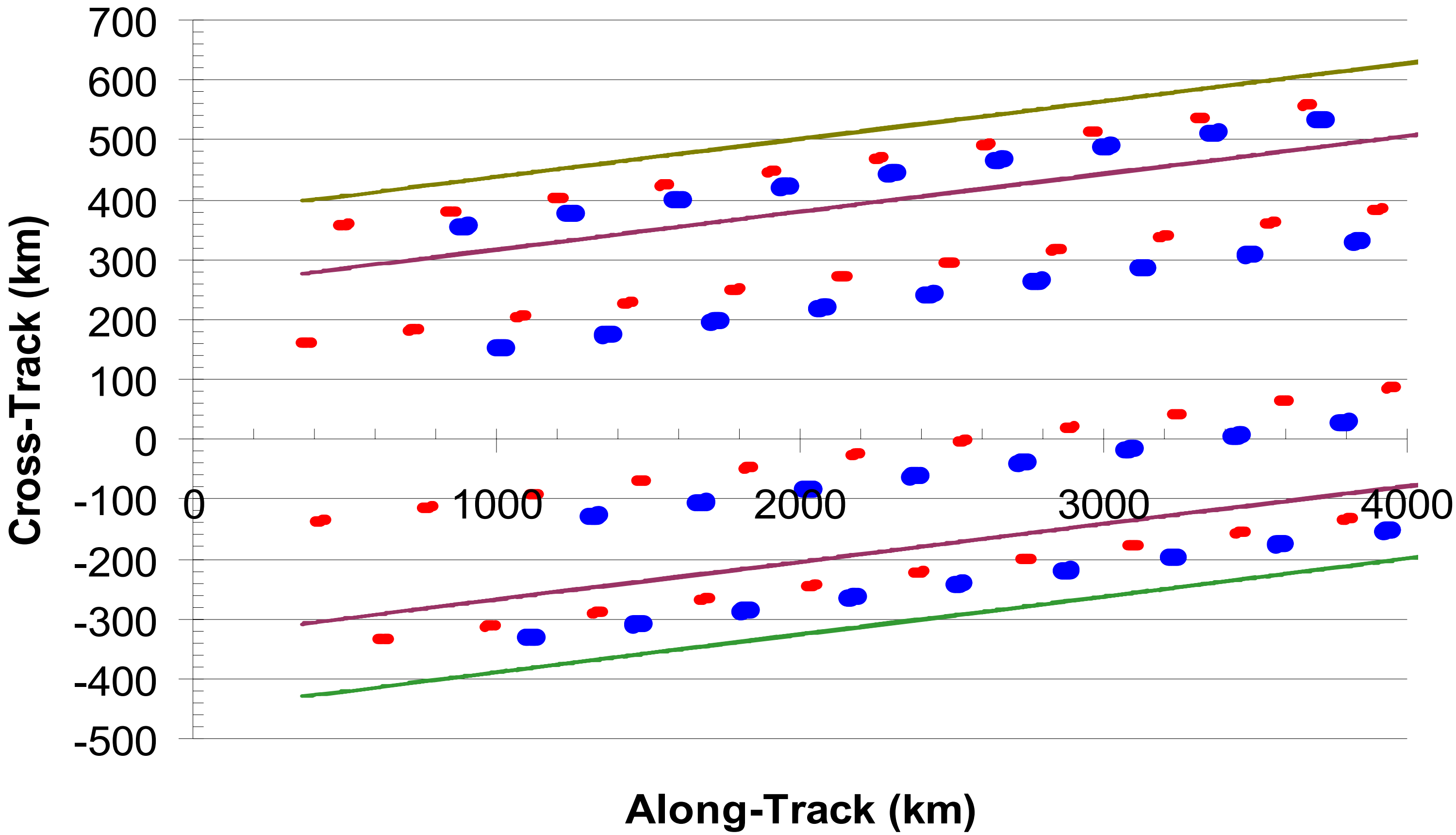
| β model | β percentile | CDWL g | Altitudes Covered | Pulse Energy, J |
|---|---|---|---|---|
| **Combined** | 50% | 90% | 0-2, 10-20 | 2.4 |
| **Combined** | 60% | 84% | 0-2, 10-20 | 2.5 |
| **Combined** | 70% | 72% | 0-2, 10-20 | 2.4 |
| **Combined** | 80% | 63% | 0-2, 10-20 | 2.5 |
| **Combined** | 90% | 56% | 0-2, 10-20 | 3.0 |
| | | | | |
| Background | 50% | 90% | 0-2, 10-20 | 2.6 |
| **Combined** | 50% | 90% | 0-2, 10-20 | 2.4 |
| Enhanced | 50% | 90% | 0-2, 10-20 | 2.0 |
| Background | 90% | 56% | 0-2, 10-20 | |
| **Combined** | 90% | 56% | 0-2, 10-20 | |
| Enhanced | 90% | 56% | 0-2, 10-20 | |

Need 1/2 the pulse energy

Slightly misses science requirements

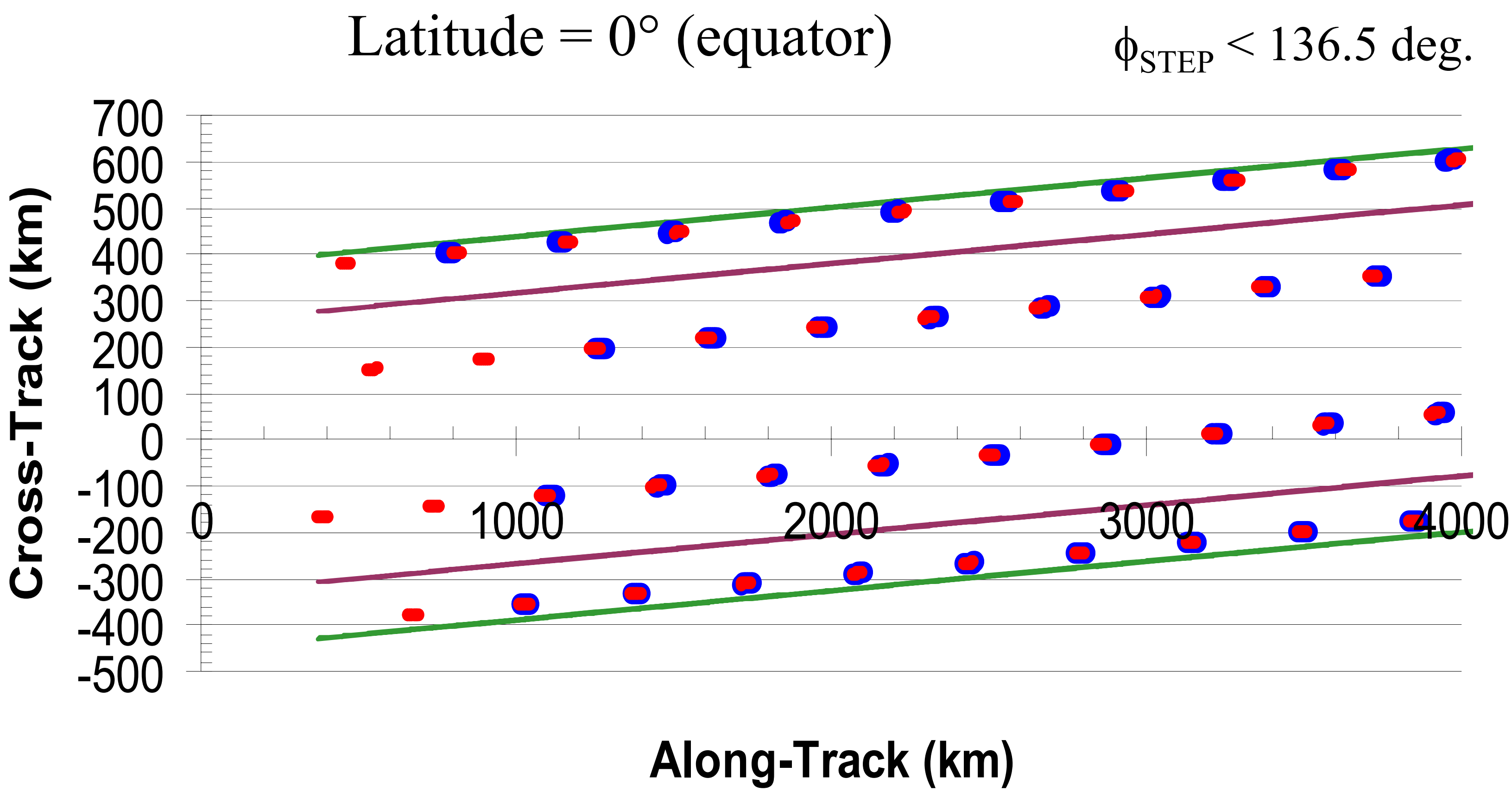
**400 km orbit, 45 degree nadir angle**
**CCW sequential azimuth pattern**
**21.3, 57.8, 122.2, 158.7, -158.7, -122.2, -57.8, -21.3**
**Symmetric in cross-track. 1.06 sec. to scan.**

Latitude = 0° (equator) $\phi_{STEP}$ < 64.4 deg.




 Fails: need 35 km or better coincidence of two perspectives 

## 400 km orbit, 45 degree nadir angle
## Non-sequential azimuth pattern
## 114, 73.8, -18.4, -155, -109, -64.2, 25.3, 152
## Non-symmetric in cross-track. 1.06 sec. to scan.




Success, but must tweak pattern vs. latitude

# Future Point Design Refinements

- 2-micron laser capable of double pulsing; 2 pulselets/pulse
- Smaller search bandwidth
- Dual balanced heterodyne detection
- Cloud top winds
- More enhanced aerosol backscatter

↑ Smaller Lidar

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↓ Larger Lidar

- Wind shear
- Laser frequency uncertainty
- Spacecraft velocity uncertainty
- Less enhanced aerosol backscatter
- Possible scanner aperture loss
- Refractive beam bending
- Possible wind-backscatter correlations

# Recommendations

**ANALYSIS**

- Develop a Monte Carlo performance simulation to properly handle coherent detection statistics, aerosol backscatter statistics, cloud statistics, and wind shear magnitude and direction statistics – IN PROGRESS BY GTWS
- Develop a simulation to relate optical aberrations of opt. components to SNR loss
- Locate experimental data which provides aerosol backscatter $\beta$ profile shape from ground to stratosphere, and apply shape to extend GLOBE data upwards
- Refine probability density function of $\beta$
- Commission a pointing control/knowledge study
- Reexamine science requirements for application to a hybrid DWL
- Develop an optimum hybrid point design
- Conduct an ISAL/IMDC exercise for a hybrid DWL in space

**EXPERIMENT**

- Experimentally confirm DWL performance prediction equations

**DEVELOPMENT**

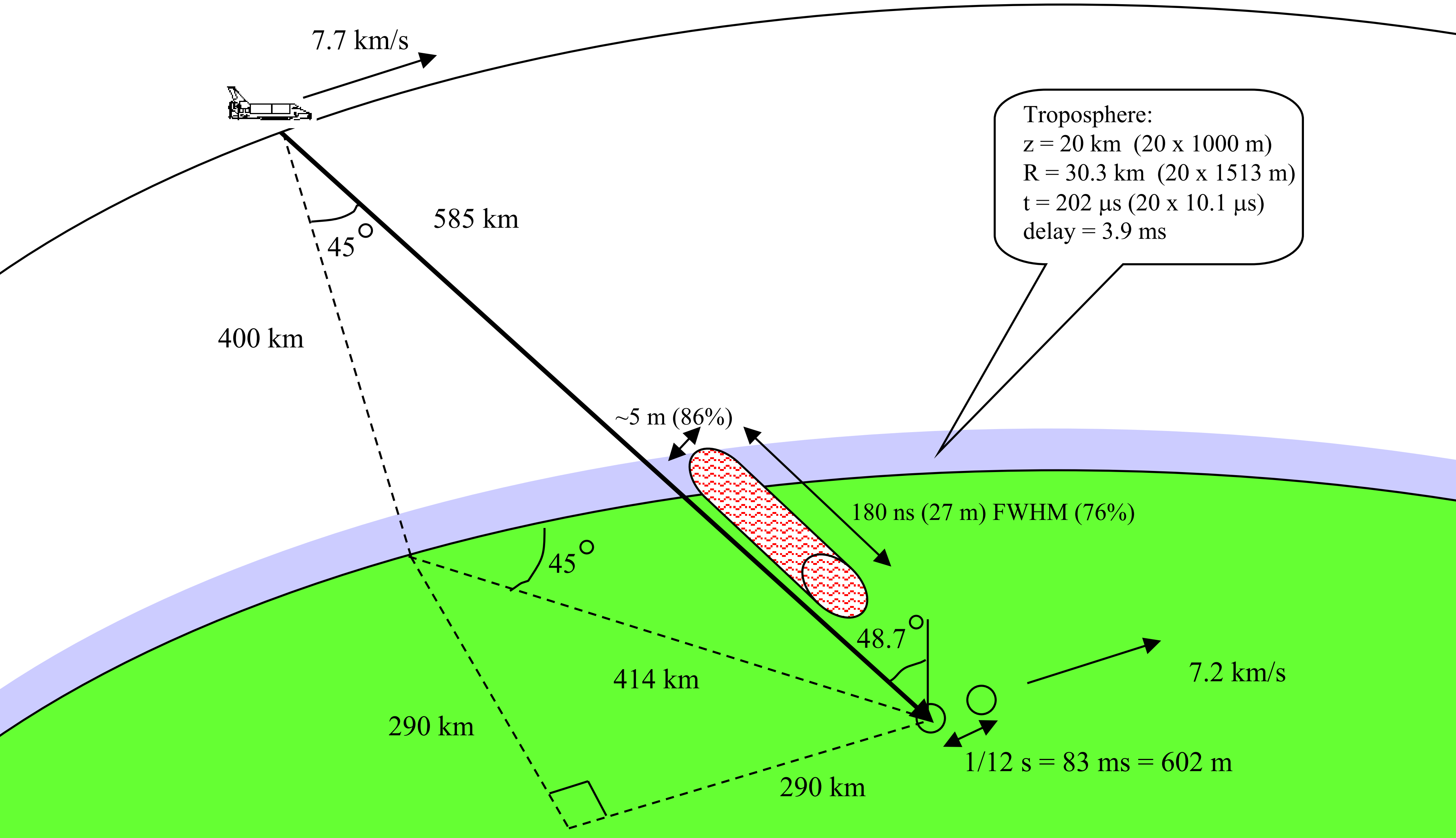
- Develop tall pole technologies and demonstrate their operation

**DEMONSTRATION**

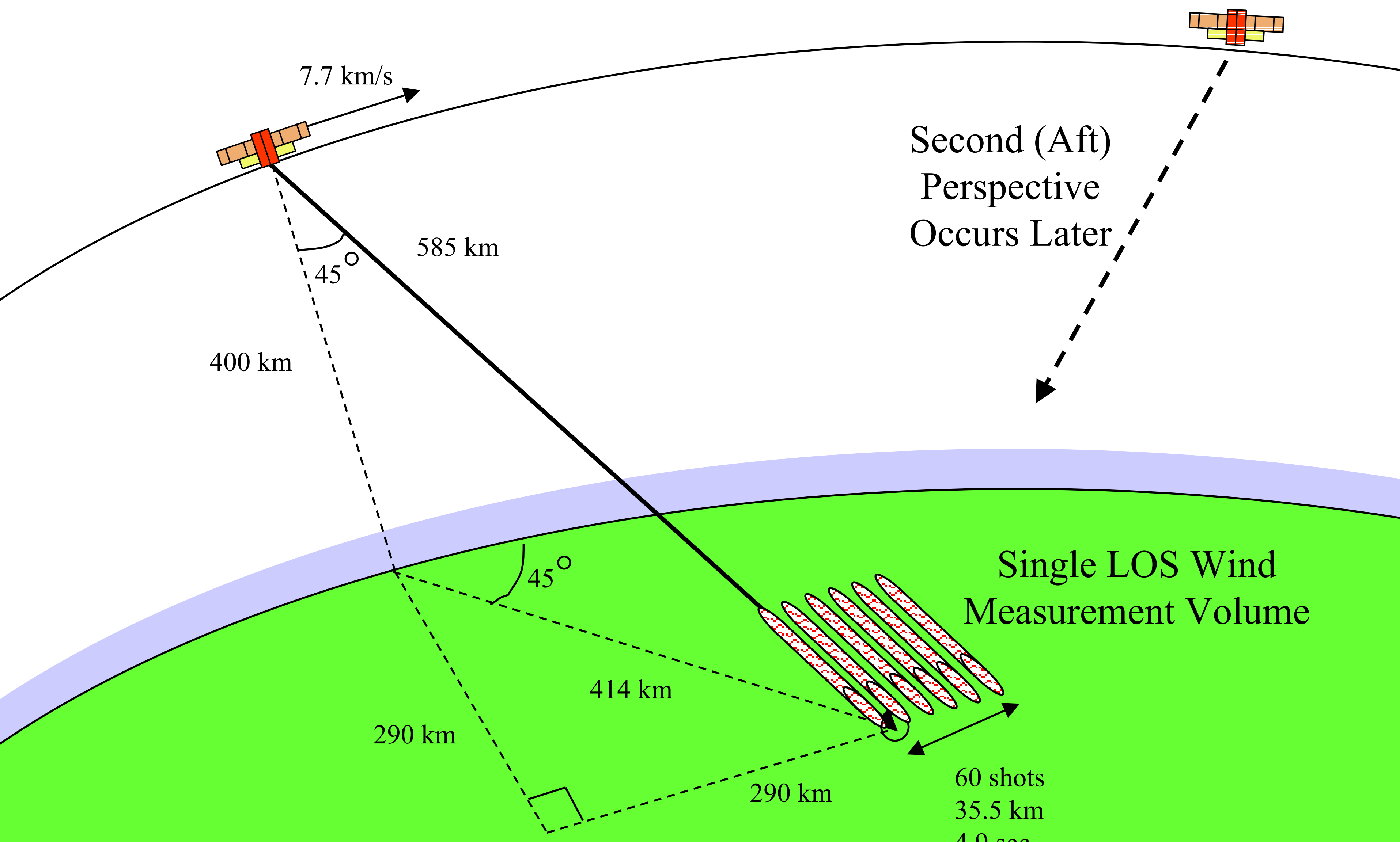
- Pursue a technology and technique demonstration in space

# Back Up Slides

# Coherent Doppler Wind Lidar Space-Based Measurement



# Coherent Doppler Wind Lidar Space-Based Measurement

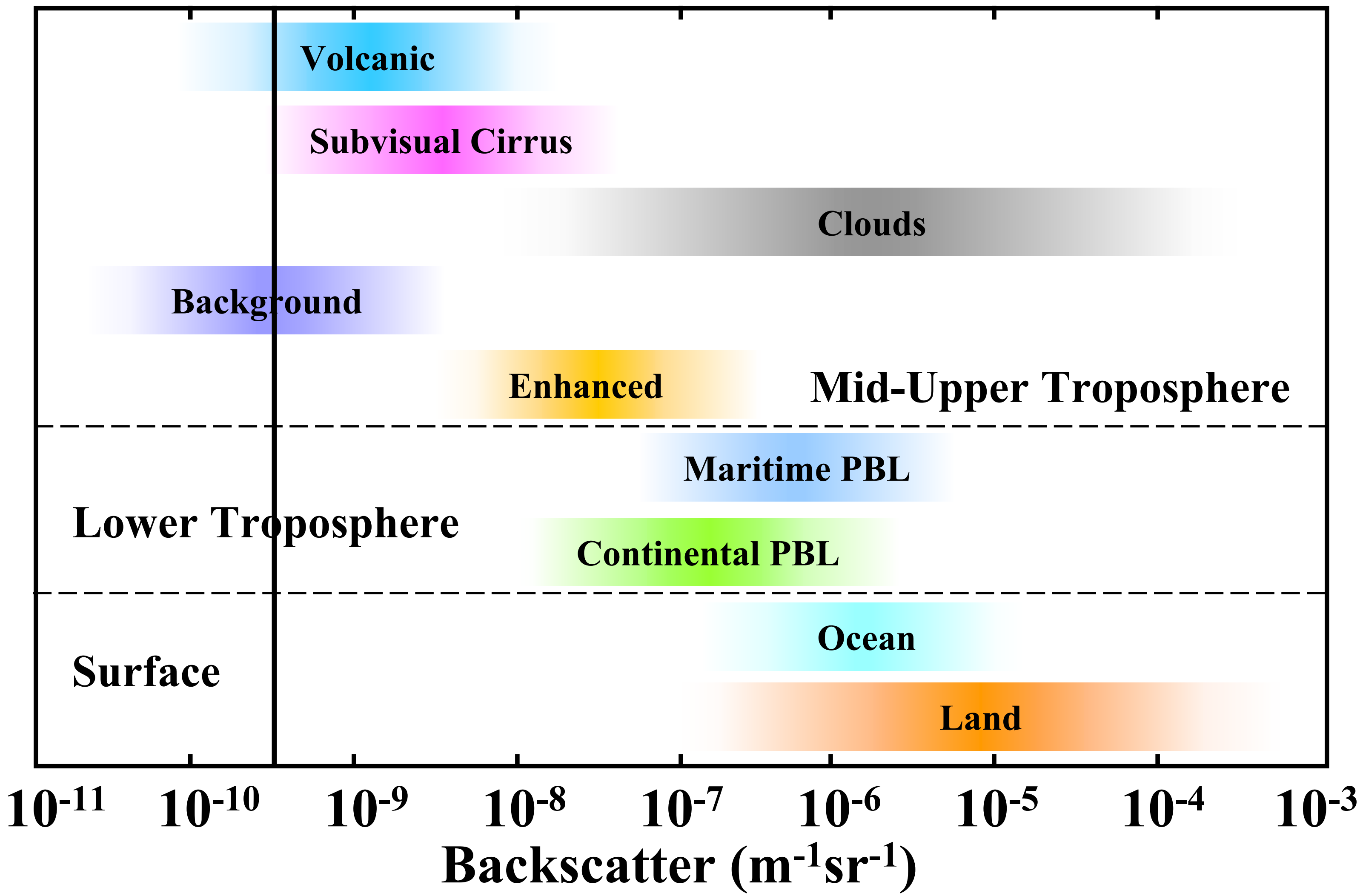


# Good And Bad Wind Velocity Estimates From Coherent Doppler Lidar

- Statistical process decides percentage of attempts which are good and bad (applies to each range gate of each shot)
- Good wind estimates ALL have low velocity error $\sigma_G$, truly "good"
- Bad wind estimates (duds) are uniformly distributed over velocity search space; therefore misleading to discuss a $\sigma_B$ velocity error for these
- SNR dramatically changes percentages of good and bad, and gently changes $\sigma_G$ of good wind estimates

R. M. Hardesty, IEEE Trans. on Geoscience and Remote Sensing GE-24, 777 (1986).
R. G. Frehlich & M. J. Yadlowsky, J. Atmos. & Oceanic Tech. 11, 1217 (1991).

# Natural Variability of 2 μm Backscatter



# CDWL POINT DESIGN ASSUMPTIONS - 5

- Constant aerosol backscatter coefficient, no fluctuations
- $50^{th}$ percentile value of wind turbulence spectrum (50% of atmosphere has more turbulence)(from GASP aircraft data)
- Kolmogorov horizontal wind field spectrum
- 0 m/s per km of linear wind shear (horizontal wind change in vertical direction in plane of lidar beam)
- 0 m/s $\sigma$ of velocity error due to fluctuations of transmitter laser to LO laser frequency difference
- No vertical velocity or velocity fluctuations
- Capon spectral estimator

# Coherent Doppler Wind Lidar SNR Equation

- $$SNR_W = \frac{E\,A\,(LSE)\,T_A^2\,\beta\,c\,\eta_{MIS,S}}{h\nu(2B_{VS}/\lambda)\,2\,R^2}$$

$\nu = c/\lambda$ $B_{fS} = 2B_{VS}/\lambda$ $A = \pi D^2/4$

LIDAR ATMOSPHERE

Frehlich and Kavaya, Appl. Opt. 30, 5325 (1991). Eqs. (92, 117, 119)

# How Aerosol Backscatter Sensitivity Is Affected By Range Resolution And Shot Accumulation

$$\beta_{sens} \propto \frac{R^2}{E\ A\ (LSE)\ T_A^{\,2}\ \eta_{MIS,S}\ \mathrm{SQRT}[N_{shot} * R_{res}]}$$

Range Resolution

Shot Accumulation

LIDAR ATMOSPHERE

B. J. Rye & R. M. Hardesty, IEEE Trans. On Geoscience & Remote Sensing 31, 16 (1993).
R. Frehlich, J. Appl. Meteorol. 39, 245 (2000).

# Two Figures Of Merit For Wind Measurement

$$g = 1 - \mathrm{EXP}[-(\Phi/b_0)^{\alpha}]$$ Prob. good estimate [-]

$$\sigma_g = \chi[1 + (\Phi/g_0)^{\varepsilon}]^{-\delta} + \mu$$ Error std. dev. of good estimates [m/s]

$\Phi = M \times SNR_W$ $\quad M \times T_S = T_{RES}$ $\quad T_{RES} = (2/c)R_{RES}$ $\quad R_{RES} = Z_{RES}/\cos\Theta_{NT}$

$T_S = 1/B_{fS}$ $\quad B_{fS} = 2\,B_{VS}/\lambda$ $\quad \nu = c/\lambda$ $\quad A = \pi D^2/4$

$$\Phi = \frac{E\,A\,(LSE)\,T_A^{\,2}\,\beta\,R_{RES}\,\eta_{MIS,S}}{h\nu R^2}$$

# Velocity Estimator Parameters

## No wind shear

| z | $b_0$ | $\alpha$ | $\chi$ | $g_0$ | $\varepsilon$ | $\delta$ | $\mu$ |
|---|---|---|---|---|---|---|---|
| 0-2 km | 1.552 | 1.578 | 0.953 | 1.779 | 3.303 | 0.3122 | 0.0454 |
| 3-20 km | 1.496 | 1.613 | 1.045 | 1.577 | 3.342 | 0.2969 | 0.0215 |

## 5 m/s/km wind shear

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0-2 km | 1.591 | 1.555 | 0.998 | 1.929 | 4.567 | 0.2229 | 0.0511 |
| 2-20 km | 1.579 | 1.477 | 1.373 | 2.385 | 3.066 | 0.3515 | 0.0336 |

# The CDWL Performance Cliff

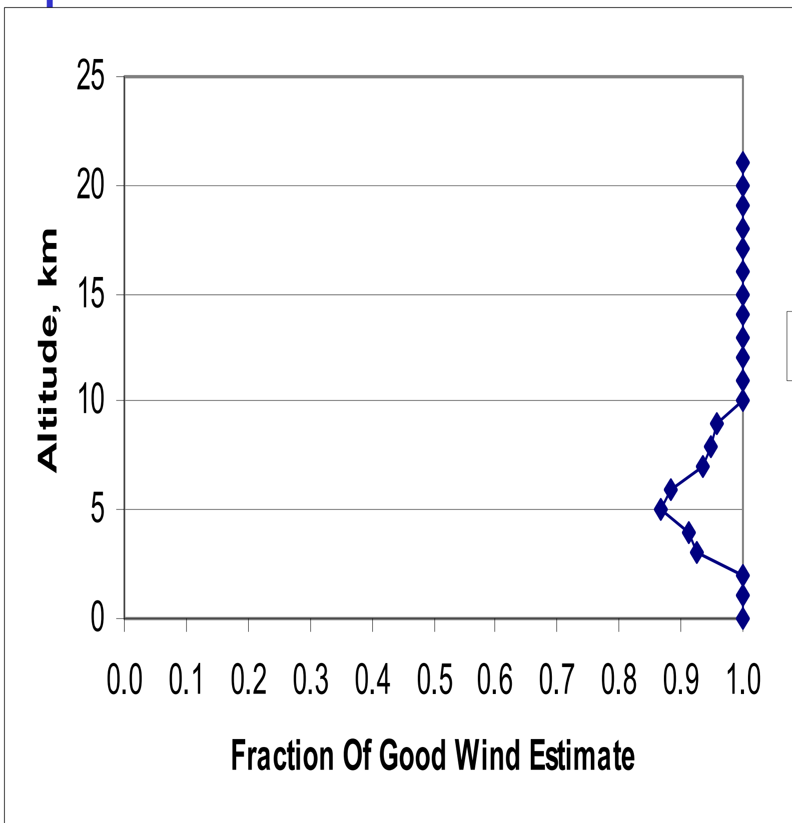
- Dramatic performance change over ~ factor of 10 in aerosol backscatter β (or any SNR factor)
- Science Requirements: "A threshold fraction of 50% of all the wind observations made … must meet the standards"
- Showing performance for median β open to criticism of too optimistic since a significant portion of the atmosphere has lower β
- Showing performance for 90 percentile β open to criticism of too pessimistic since ~90% of atmosphere has higher β; and other percentiles were not provided
- Difficult to be precise with deterministic simulation given current knowledge of global distribution of 2-micron backscatter
- Recommend a Monte Carlo simulation be developed

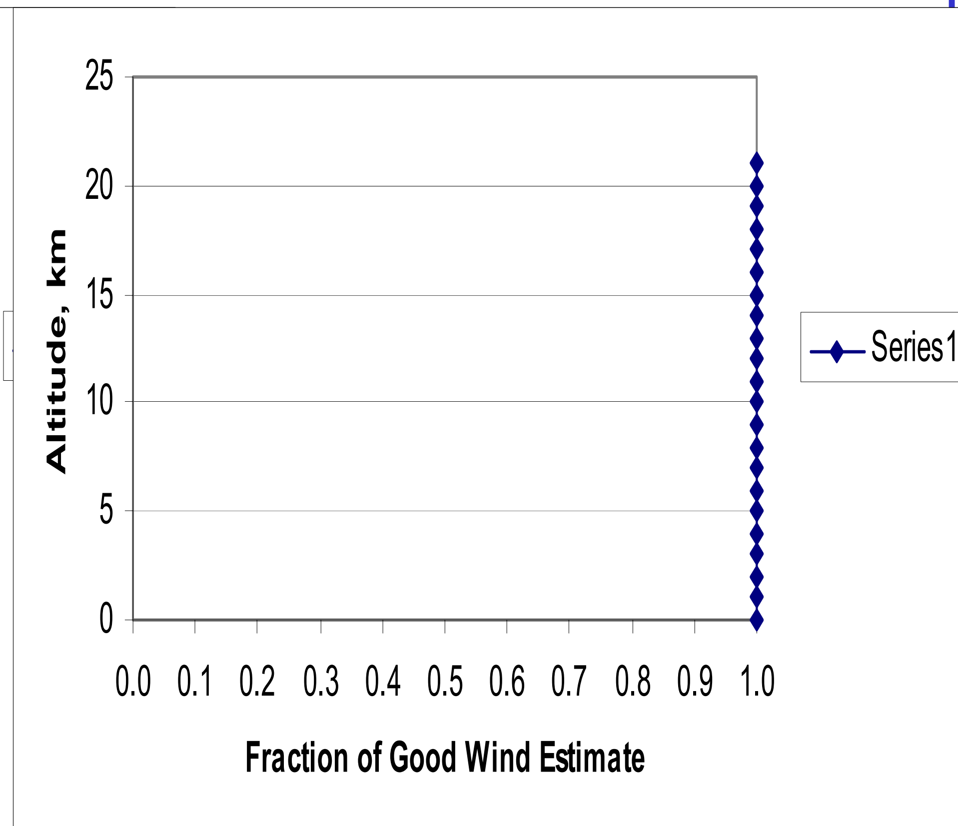
# How Many 50%'s Are There?

- Backscatter percentile is a percent, 50% provided
- Wind turbulence value assumed at 50%
- Misalignment loss assumed at 50%
- Coherent lidar probability of good is a percent
- Science requirement: fraction good > 50%
- Bottom cloud layer blocks 50% of shots
- Combining background and enhanced backscatter involves percents

# CDWL POINT DESIGN RESULTS - g

Background, 50th      5.0 J      Enhanced, 50th



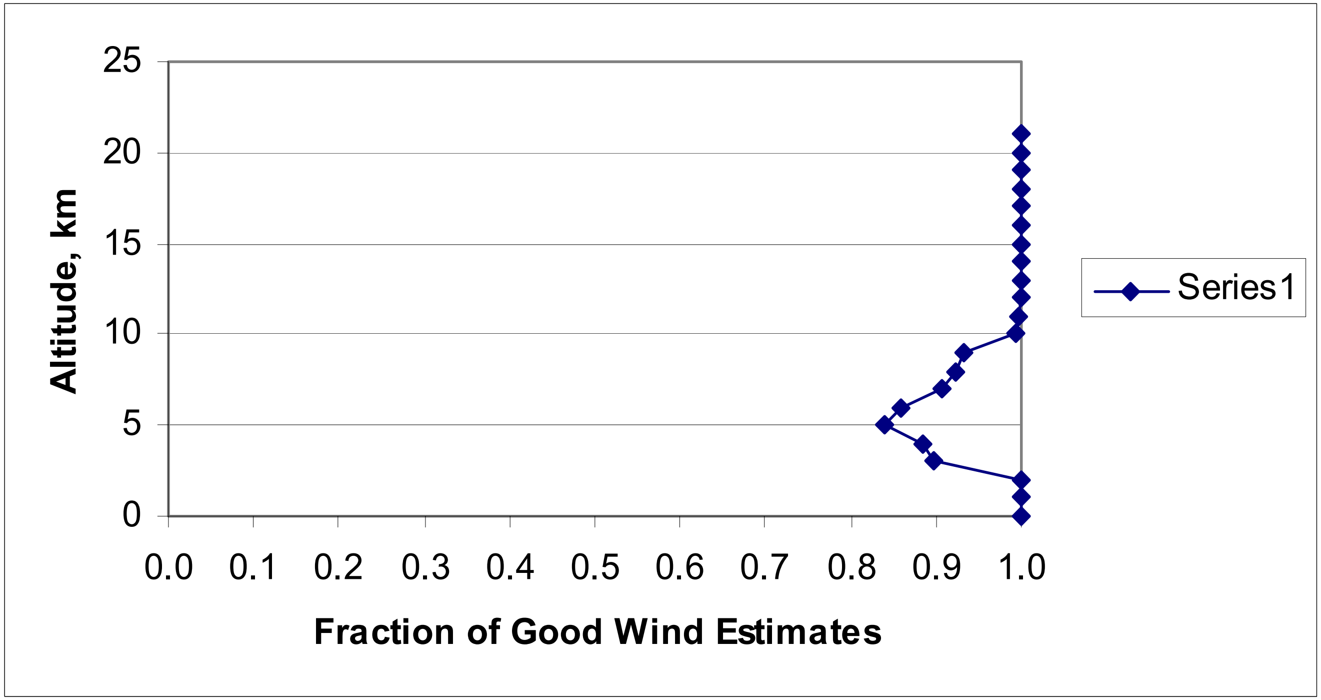
# CDWL POINT DESIGN RESULTS - g

## 5.2 J

Assume: 75% Background (60th); 25% Enhanced (60th)

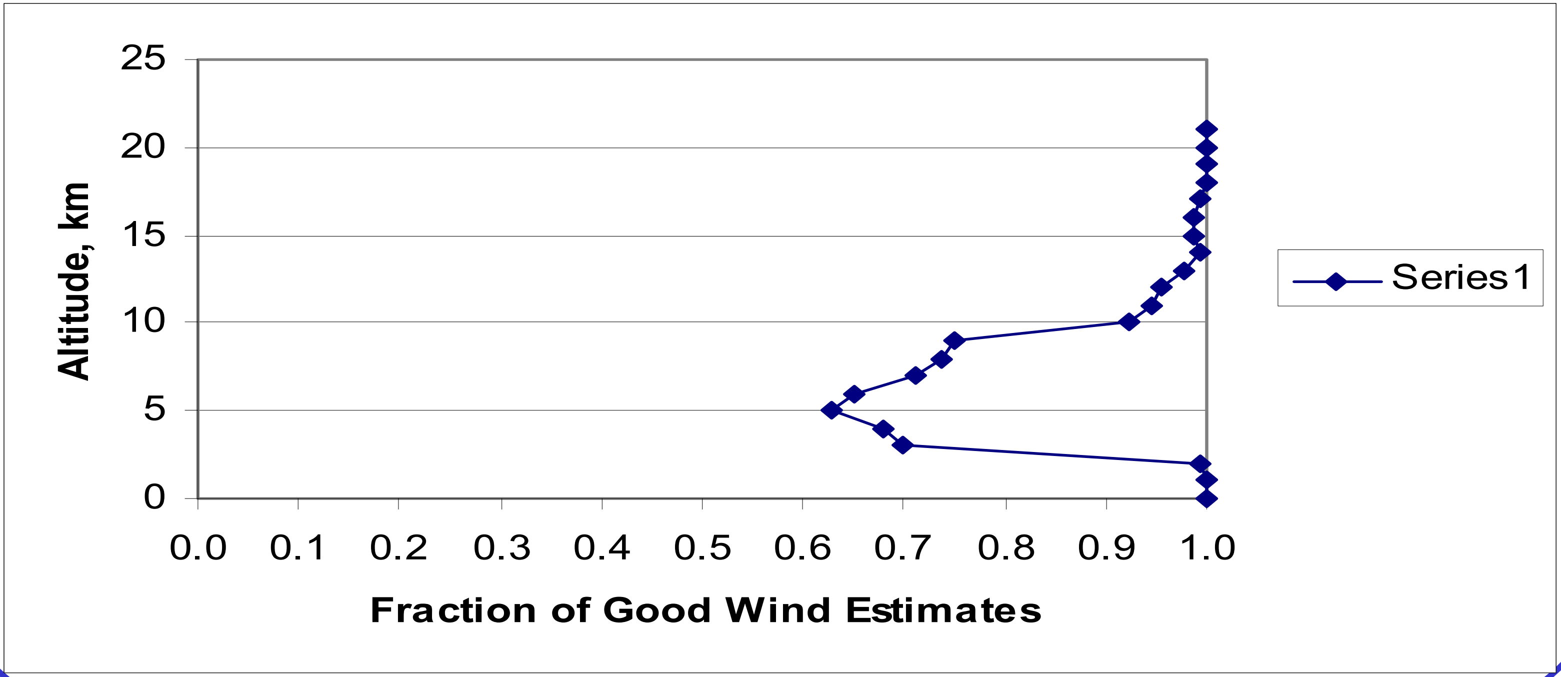
Background x 0.82; Enhanced x 0.78

g > 0.84 because 0.60 x 0.84 = 0.504 > 0.5



# CDWL POINT DESIGN RESULTS - g
5.2 J

Assume: 75% Background (80th); 25% Enhanced (80th)
Background x 0.51; Enhanced x 0.43
g > 0.63 because 0.80 x 0.63 = 0.504 > 0.5



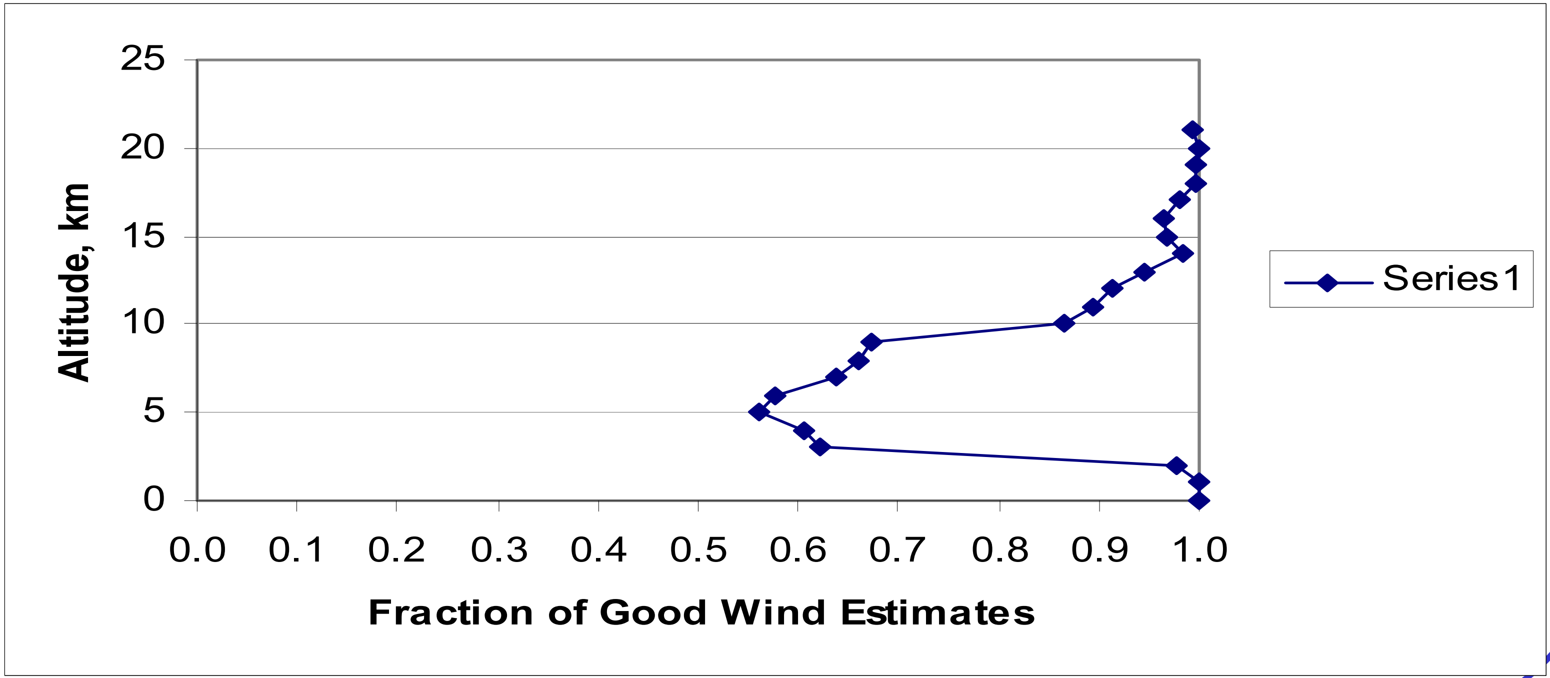
# CDWL POINT DESIGN RESULTS - g

6.2 J

Assume: 75% Background (90th); 25% Enhanced (90th)

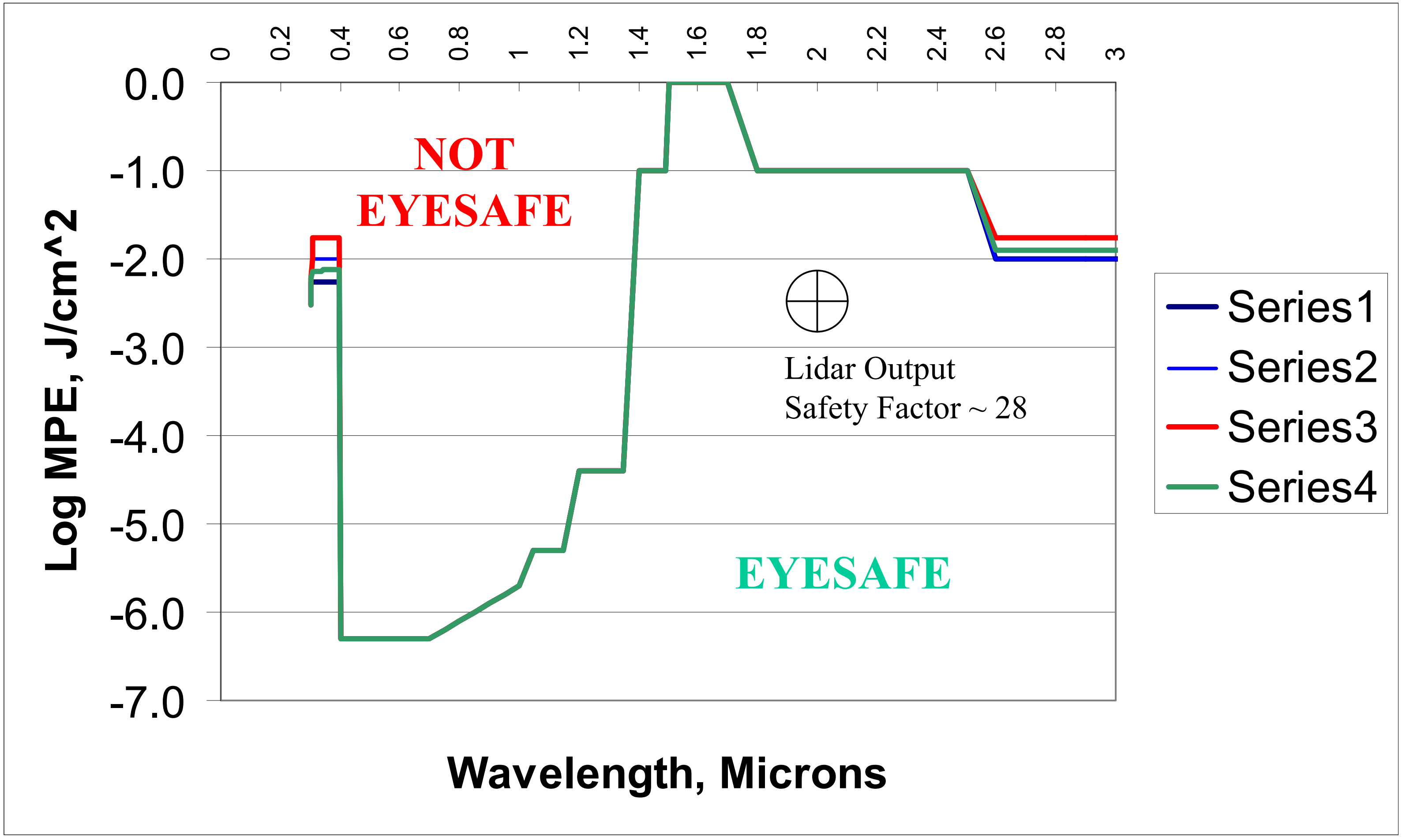
Background x 0.36; Enhanced x 0.28

g > 0.56 because 0.90 x 0.56 = 0.504 > 0.5



# Eye Safety Analysis at 5 J

ANSI Z136.1 – 2000




Laser Pulse Durations: 10 ns, 100 ns, 1000 ns, (λ/2 [microns])(180 ns)

# DWL Scan Patterns

- Spherical earth
- Rotating earth
- Sun-synchronous 400 km orbit (retrograde)
- 97.03° orbit inclination angle
- S/C heading NW
- Fore shots blue, aft shots red
- Maximum scanner reach green
- CT positions with 90° dual perspective angles brown
- +AT axis in forward direction
- +CT axis in left direction
- AT/CT axes shown apply to first lidar shot
- +Azimuth angle CCW from forward

# Data Rate

- Downlink all raw data
- Signal bandwidth = 168 MHz [wind speed range (110), angle knowledge errors, etc.]
- Buffer from DC = 12 MHz
- ADC sampling rate = 360 MHz
- Captured altitudes = -1 to 21 km
- 8 bits/sample
- 7.7 Mbit/s = 42.5 Gbit/orbit

# Questions

- May the 50% or less wind measurement attempts that fail be grouped by height, location, etc.?