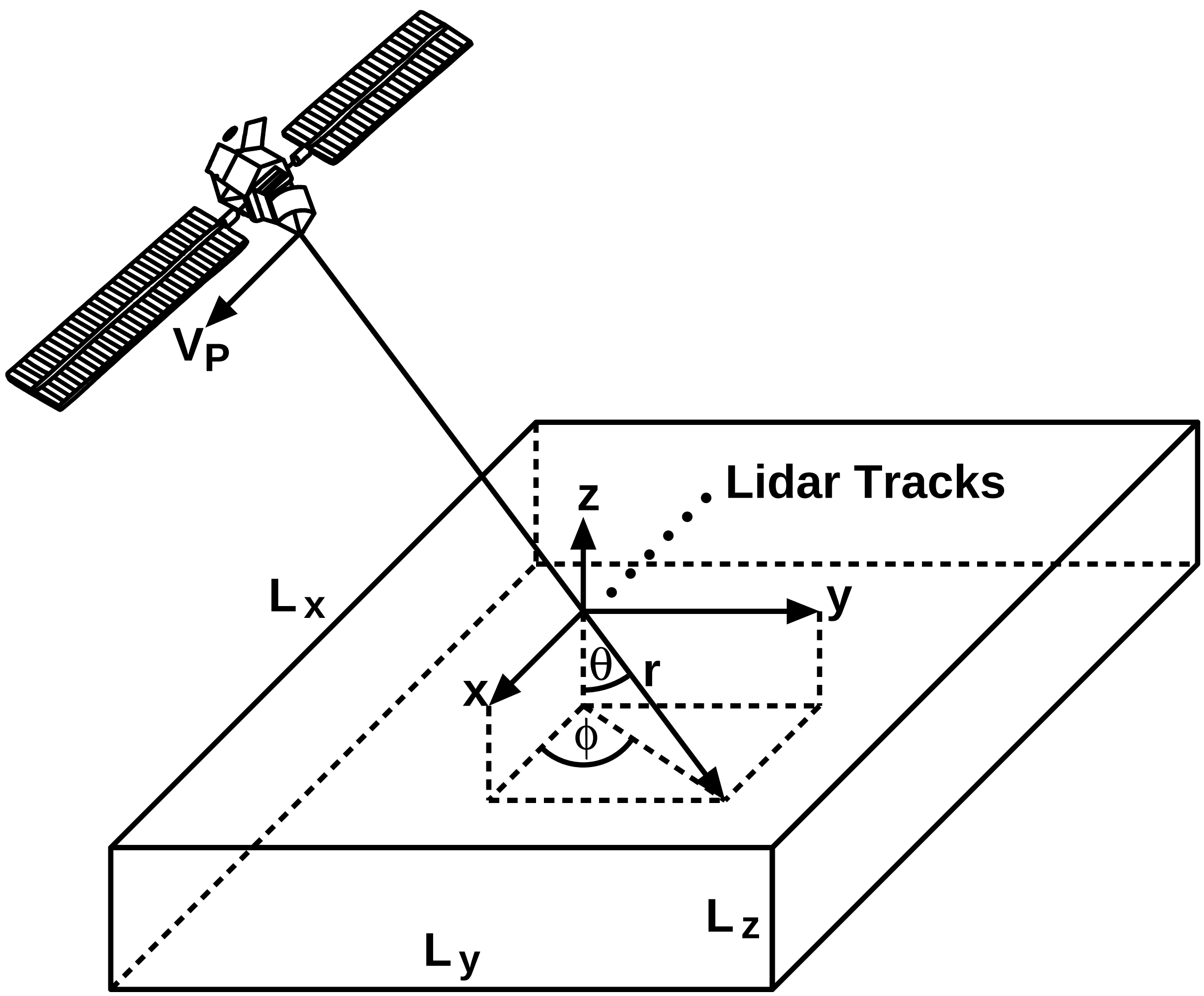
Verification of Doppler Lidar Velocity Error

Rod Frehlich and Robert Sharman
National Center for Atmospheric Research (NCAR)
Boulder, CO 80307

Funded by the FAA Aviation Safety Program
and by NASA, Technical Officer
Michael J. Kavaya, NASA Langley

Email: rgf@cires.colorado.edu

Schematic of a Space-Based Doppler Lidar



DEFINITION OF VELOCITY ACCURACY

- **Velocity field is random**

- **Definition of velocity accuracy requires definition of truth "m"**

- **Accuracy composed of bias and random error e**

$$\hat{\mathbf{v}} = \mathbf{m} + \mathbf{e} + \mathbf{BIAS}$$

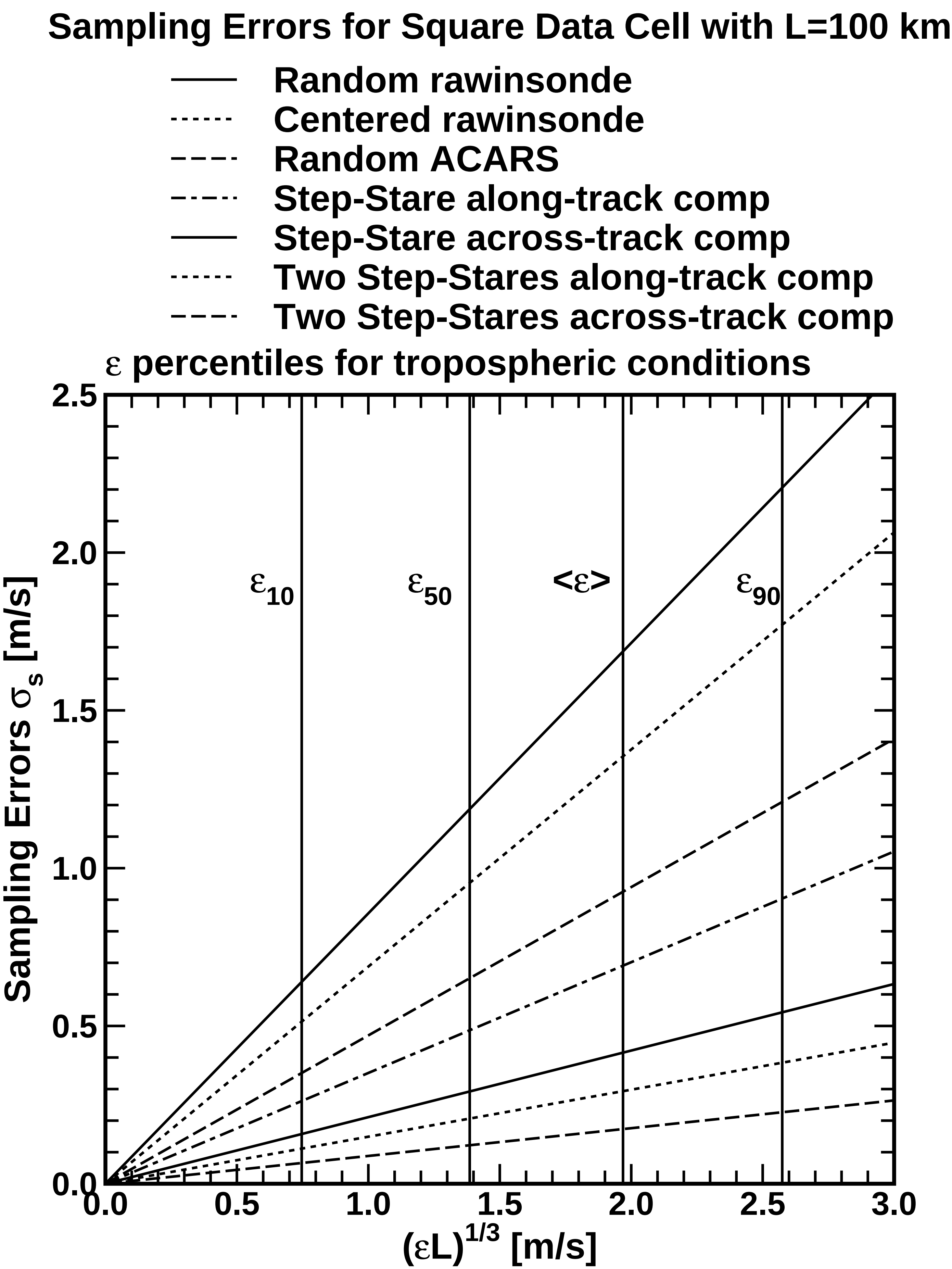
- **Bias of estimate = $< \hat{v} - m >$**
  $< x >$ denotes ensemble average of x over the random windfield

- **Random error $\sigma^2 = < [\hat{v} - < \hat{v} >]^2 >$**

- $\sigma^2 = \sigma_m^2 + \sigma_s^2$

σ_s **- representative error**

σ_m **- instrument and estimation error**


Sampling Errors for Square Data Cell with L=100 km
Random rawinsonde
Centered rawinsonde
Random ACARS
Step-Stare along-track comp
Step-Stare across-track comp
Two Step-Stares along-track comp
Two Step-Stares across-track comp
ε percentiles for tropospheric conditions
ε10
ε50
<ε>
ε90
Sampling Errors σs [m/s]
(εL)1/3 [m/s]
0.0
0.5
1.0
1.5
2.0
2.5
3.0

SPACE-BASED VELOCITY MEASUREMENTS: MULTIPLE-SHOT FIXED STARE

- Radial velocity is produced from accumlated data from N lidar shots

- True velocity m is the average of the radial velocity $v_r(x, z)$ over the measurement plane

$$m = \frac{1}{L_z L_x} \int_{z=0}^{L_z} \int_{x=0}^{L_x} v_r(x, z)\,dx\,dz$$

- Truth is the same for any shot number N

- This definition of truth separates representative error from instrument error

- Performance depends on the spatial statistics of the velocity field over the measurement cell

- σ_{veff} is the effective rms velocity variability over the measurement plane

VERIFICATION OF RANDOM ERROR BASED ONLY ON DATA

- **Velocity measurements with N lidar shots**

- **Produce two velocity estimates with even and odd numbered pulses**

$$v_1(N/2) = m + e_1(N/2) + BIAS$$
$$v_2(N/2) = m + e_2(N/2) + BIAS$$

- **Consider the difference of the two velocity estimates $\Delta v = v_1 - v_2$**

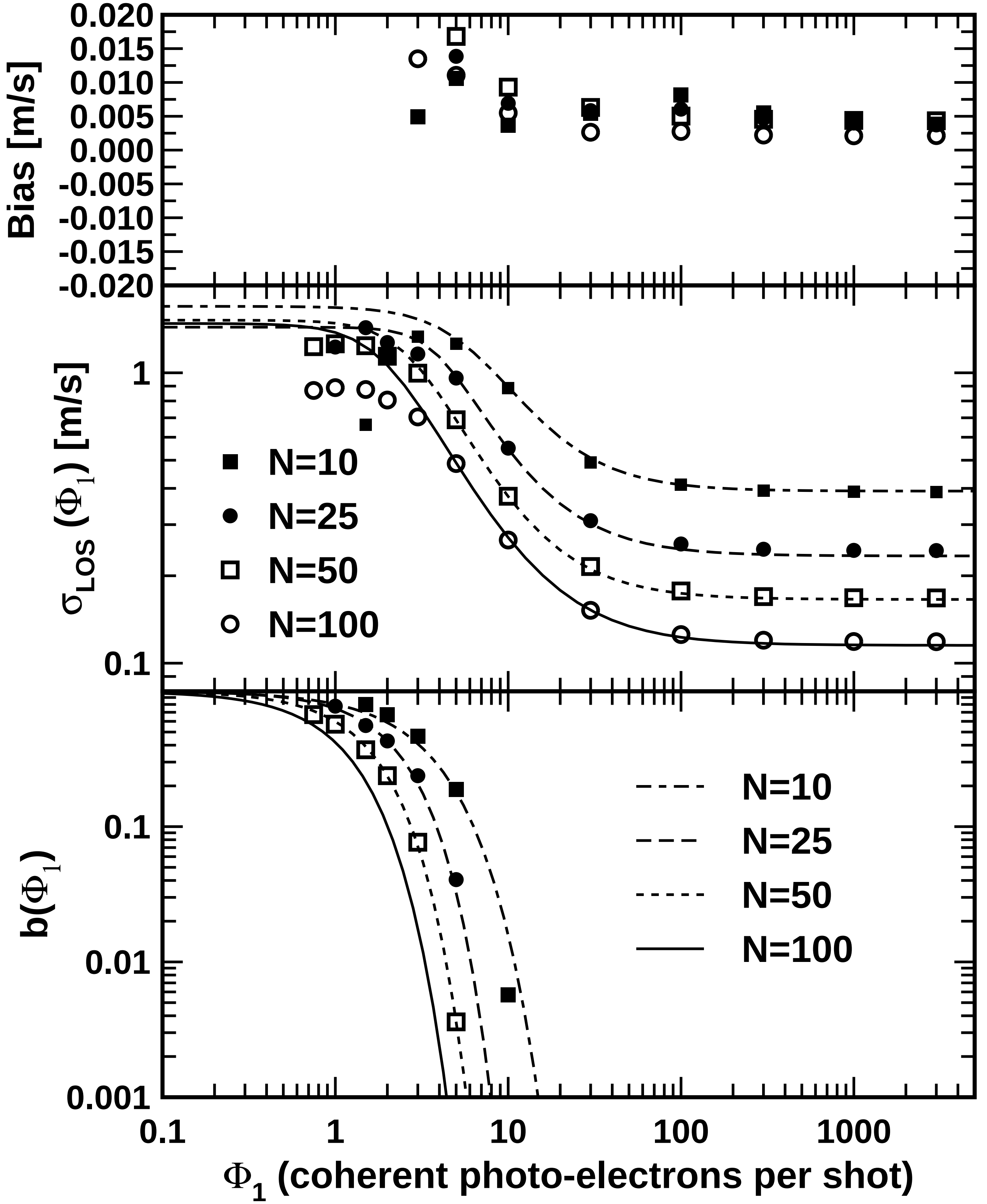
- **If e_1 is uncorrelated with e_2 then**

$$\sigma_v^2 = \langle \Delta v^2 \rangle = 2\sigma^2(N/2)$$

- **Random error for N lidar shots**

$$\sigma^2(N) = \sigma^2(N/2)/2 = \sigma_v^2/4$$

N pulse coherent Doppler lidar for average tropospheric conditions
LOS velocity error σ_{LOS} for a 100 km track
Fraction of outliers b (useful data requires b<0.1)
Symbols indicate results of verification algorithm



VERIFICATION MEASUREMENTS WITH CTI 2-μ COHERENT DOPPLER LIDAR DATA (JUNEAU AIRPORT CAMPAIGN)

- PPI scan along landing approach (17^{o} elevation)

- determine spatial statistics of velocity

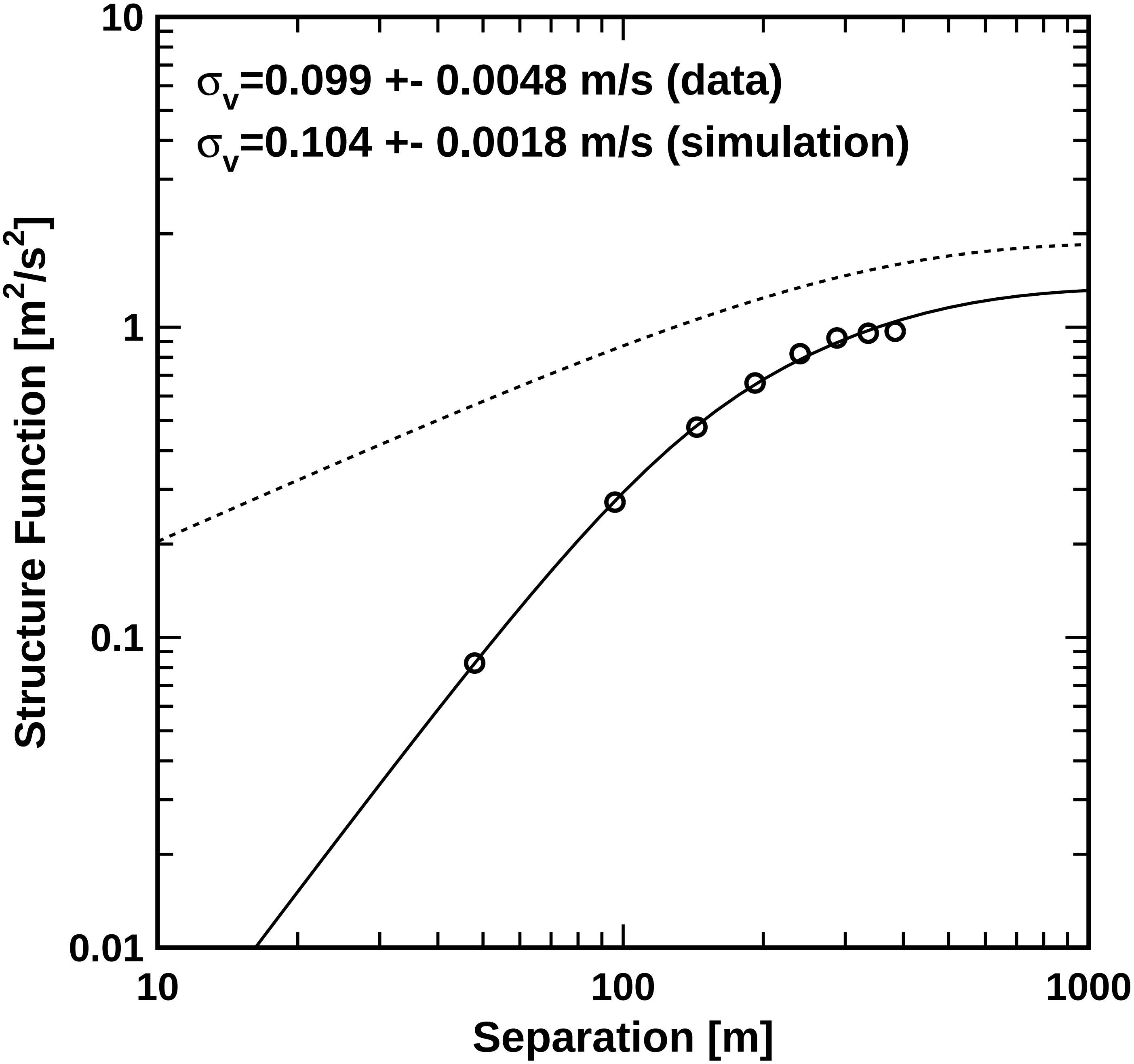
- determine velocity error

- compare with computer simulations

Data supplied by Coherent Technologies, Inc

Δp=96.0 m Δr=83.6 m Δs=48.0 m Δh=15.45 m
ε=0.00328 m^2/s^3 L_i=192.50 N=50 pulses/estimate
Measurement region= 576 m x 463 m

Best-fit von Karman model



HORIZONTAL VECTOR MEASUREMENT FROM TWO OVERLAID FOR AND AFT TRACKS

- $\hat{v}_x = (\hat{v}_{for} - \hat{v}_{aft})/2\cos(\phi)\sin(\theta)$
- $\hat{v}_y = (\hat{v}_{for} + \hat{v}_{aft})/2\sin(\phi)\sin(\theta)$

  - $\hat{v}_{for}$ = radial velocity from forward look
  - $\hat{v}_{aft}$ = radial velocity from aft look
  - θ = nadir angle
  - ϕ = azimuth angle

- LOS instrument errors are uncorrelated and equal (σ_{LOS})

- along-track error component from σ_{LOS}

$$\sigma_x = \frac{\sigma_{LOS}}{\sqrt{2}\cos(\phi)\sin(\theta)}$$

- across-track error component from σ_{LOS}

$$\sigma_y = \frac{\sigma_{LOS}}{\sqrt{2}\sin(\phi)\sin(\theta)}$$

LOW EARTH ORBIT: nadir angle $\theta = 45^{o}$

ϕ	σ_x	σ_y
10^{o}	1.015 σ_{LOS}	5.759 σ_{LOS}
20^{o}	1.064 σ_{LOS}	2.924 σ_{LOS}
30^{o}	1.155 σ_{LOS}	2.000 σ_{LOS}
45^{o}	1.414 σ_{LOS}	1.414 σ_{LOS}
60^{o}	2.000 σ_{LOS}	1.155 σ_{LOS}
70^{o}	2.924 σ_{LOS}	1.064 σ_{LOS}
80^{o}	5.759 σ_{LOS}	1.015 σ_{LOS}

NPOESS ORBIT: nadir angle $\theta = 30^{o}$

ϕ	σ_x	σ_y
10^{o}	1.436 σ_{LOS}	8.144 σ_{LOS}
20^{o}	1.505 σ_{LOS}	4.135 σ_{LOS}
30^{o}	1.633 σ_{LOS}	2.828 σ_{LOS}
45^{o}	2.000 σ_{LOS}	2.000 σ_{LOS}
60^{o}	2.828 σ_{LOS}	1.633 σ_{LOS}
70^{o}	4.135 σ_{LOS}	1.505 σ_{LOS}
80^{o}	8.144 σ_{LOS}	1.436 σ_{LOS}

SUMMARY

- **Instrument component of the random velocity error can be determined from data without supporting in situ measurements**

- **Random velocity error is dominated by atmospheric variability of velocity field and aerosol backscatter**

- **Instrument component of the random error is dominated by wind turbulence for coherent Doppler lidar space-based measurements**

- **Verification algorithm for instrument component of the random error was successfully applied to ground-based coherent Doppler lidar**

- **Nadir and Azimuth angle dependence of vector velocity error is a critical trade-off**

FUTURE WORK

- Refine requirements for bias and random error

- Determine climatology of wind variability in critical regions such as middle troposphere (wind profiler data, commercial aircraft data)

- Evaluate performance of verification algorithms for random error under various conditions

- Space-based data is critical to verify statistical behavior of Doppler lidar velocity estimates

- Leverage the work in the aviation safety program