Optical turbulence profiling at White Sands Missile Range North Oscura Peak

Dr. Matthew R. Whiteley, Rebecca L. Beauchamp, and Jonathan Diemunsch (MZA)

Dr. Richard J. Bagnell
Air Force Research Laboratory, Starfire Optical Range

November 2, 2006

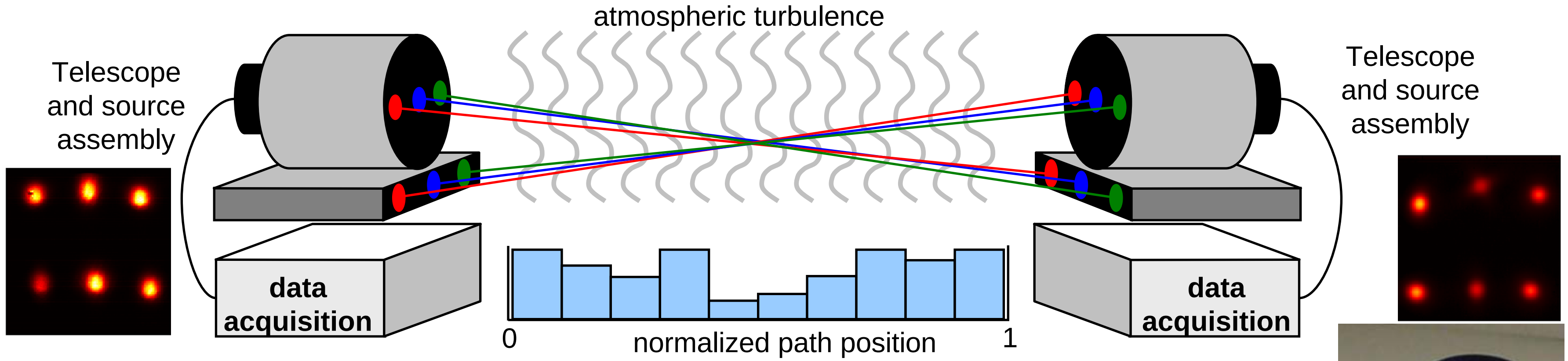
MZA Associates Corporation
6651 Centerville Business Pkwy Ste B
Dayton, OH 45459-2678
Voice: (937) 432-6560 x237

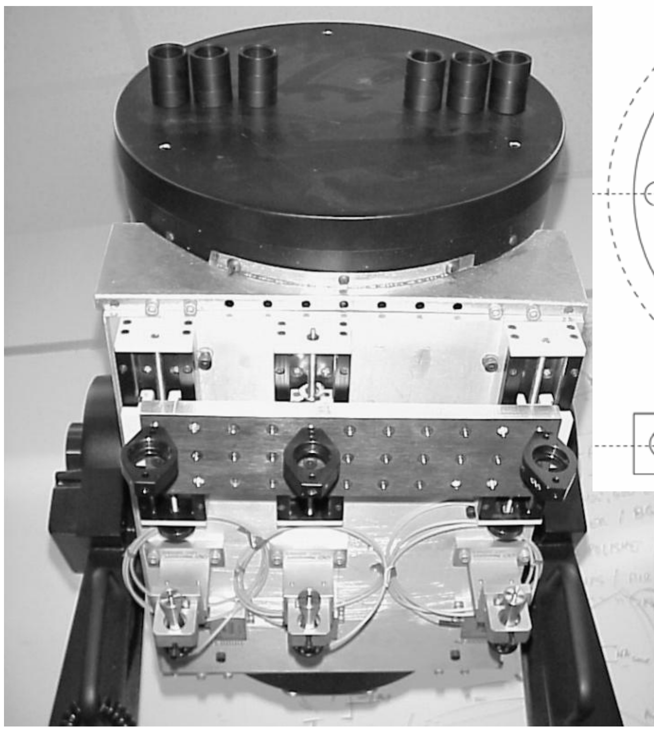
Introduction

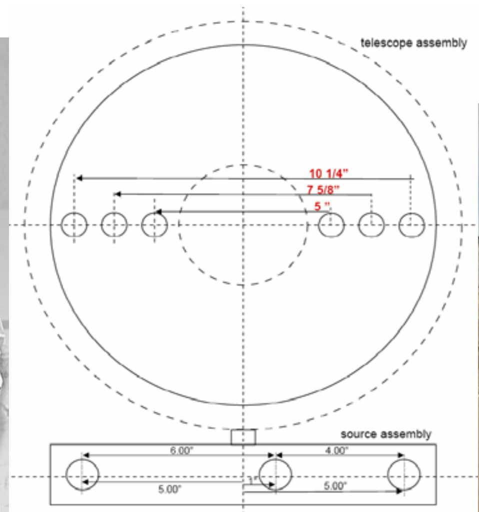
- AFRL Starfire Optical Range owns/operates a device known as the "Differential-Tilt Turbulence Profiler"
- **Development timeline**
  - 2000: AFRL/DE and AFOSR developed original concept, theory, initial design
  - 2001-2003: AFRL/DE and MZA integrated the laser & optical system, developed data acquisition software
  - 2002-2005: AFRL/DE conducted simulations, developed processing algorithms, initial testing and data analysis
  - 2006: Full-scale system test at North Oscura Peak (NOP)
- **Testing timeline**
  - 2003: NOP to Bug (~1 km), NOP to Beck (~10 km)
    - Initial data, but issue with source assembly
  - 2004: SOR to 2-mile (~3 km)
    - Revised source assembly
    - Reasonable test data and profiling results for 3 km path
  - 2005: NOP to Salinas (~50 km)
    - Poor SNR limited measurements, profiling questionable
  - 2006: NOP to Beck (~10 km)
    - Good SNR, reasonable profiles, large data volume, other diagnostics

MZA Associates Corporation

Differential-Tilt Turbulence Profiler

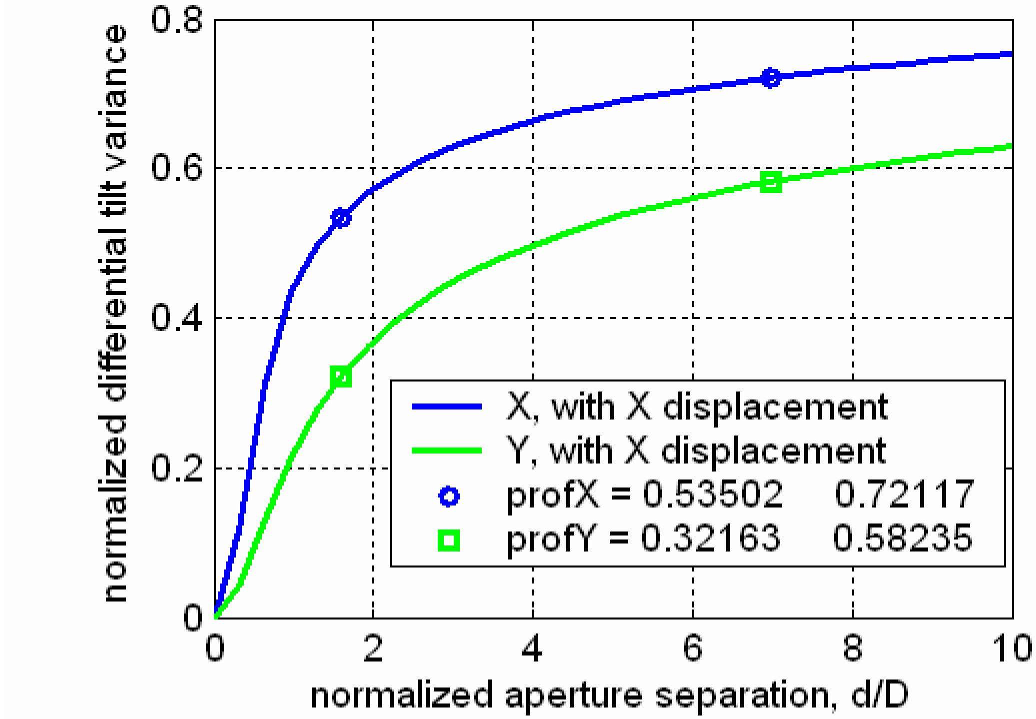






Estimation of Coherence Diameter from Profiler Centroid Data

MZA Associates Corporation



- **Can use centroid (tilt) data directly from profiler units with standard techniques for r0 estimation**
  - **Estimation from tilt-variance:**

$$\sigma_T^2 = 0.1816 D^{-1/3} \lambda^2 r0^{-5/3}$$

$$r0 = \left(\frac{\sigma_T^2 D^{1/3}}{0.1816 \lambda^2} \right)^{-3/5}$$

  - **Differential-tilt variance for 3 aperture pairs on each unit**

- **Ap-1 / Ap-2 with *s*/*D* = 1.5875 →** $\sigma_{\Delta T}^2 = 0.1943 D^{-1/3} \lambda^2 r0^{-5/3}$
- **Ap-3 / Ap-4 with *s*/*D* = 6.9850 →** $\sigma_{\Delta T}^2 = 0.2619 D^{-1/3} \lambda^2 r0^{-5/3}$
- **Ap-5 / Ap-6 with *s*/*D* = 1.5875 →** $\sigma_{\Delta T}^2 = 0.1943 D^{-1/3} \lambda^2 r0^{-5/3}$

MZA Associates Corporation

Profiler Theory of Operation

- **Profiler theory published in SPIE proceedings**
  - **Whiteley, M. R., Washburn, D. C., and Wright, L. A., "Differential-tilt technique for saturation-resistant profiling of atmospheric turbulence," *SPIE Proceedings on Adaptive Optical Systems Technology II* 4494, (2001).**
- **Difference of differential-tilt variances define measurement set that can be related to turbulence distribution over path**

$$\text{continuous: } m_k = \int_0^1 \mathrm{d}\xi \; C_n^2(\xi L) \; w_{\delta k}(\xi)$$

$$\text{discrete: } m_k = \sum_{i=1}^{N} C_{ni}^2 \, p_{ki} \rightarrow \mathbf{m} = P\mathbf{c}$$

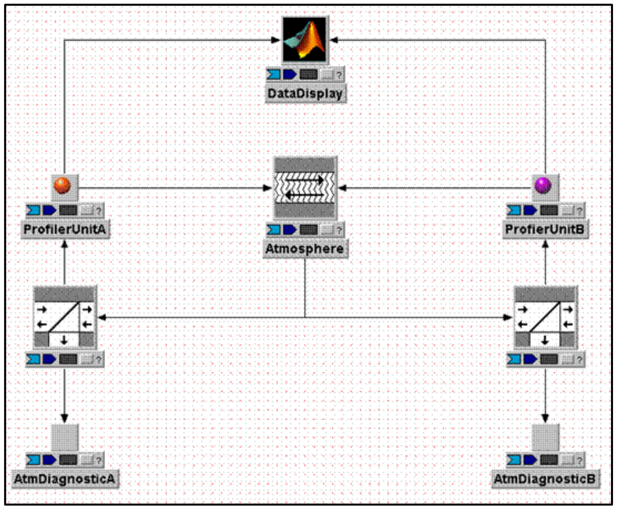
- **Relation can be inverted through appropriate numerical technique**
- **Constraints can be applied to inversion using r0 estimates for profiler used as differential-image-motion monitor**

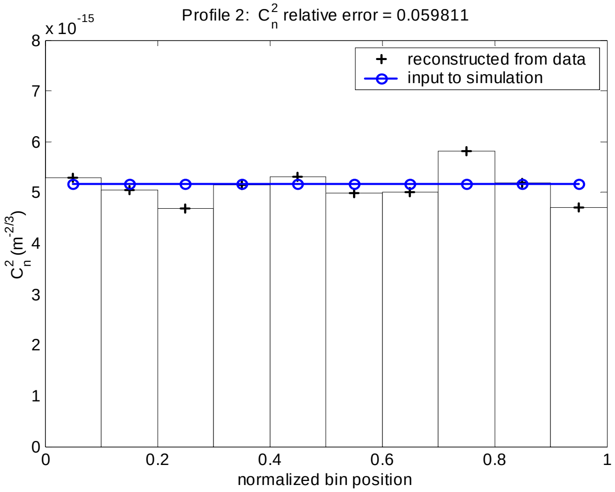
$$\mathbf{c} = (P^T P)^{-1}(P^T \mathbf{m} + \lambda_A \mathbf{w}_{r_A} + \lambda_B \mathbf{w}_{r_B})$$

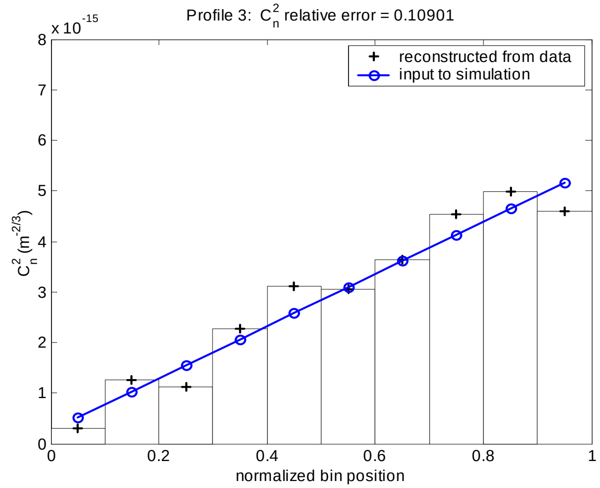
MZA Associates Corporation

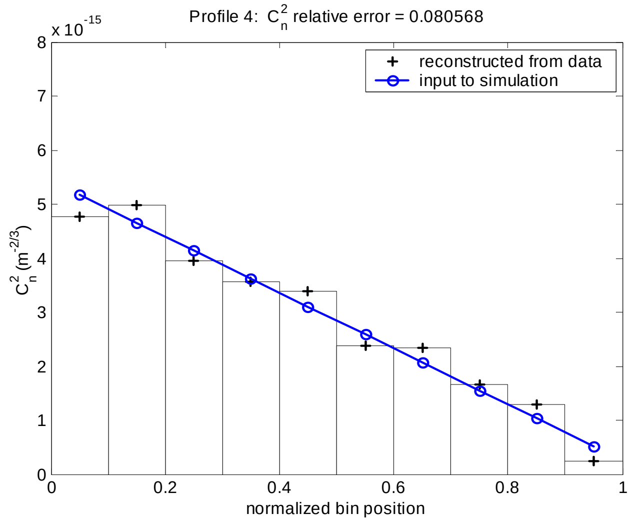
Wave-Optics Simulation of Turbulence Profiling

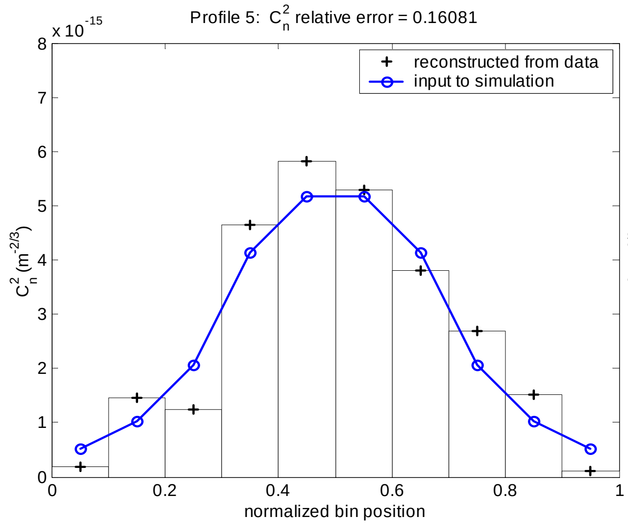
WaveTrain System Model

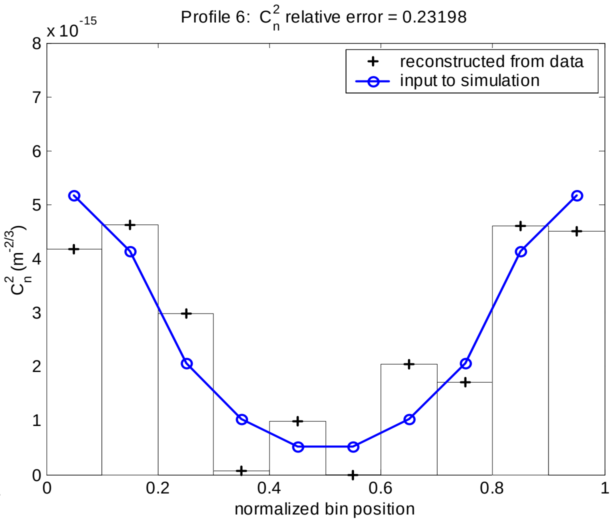










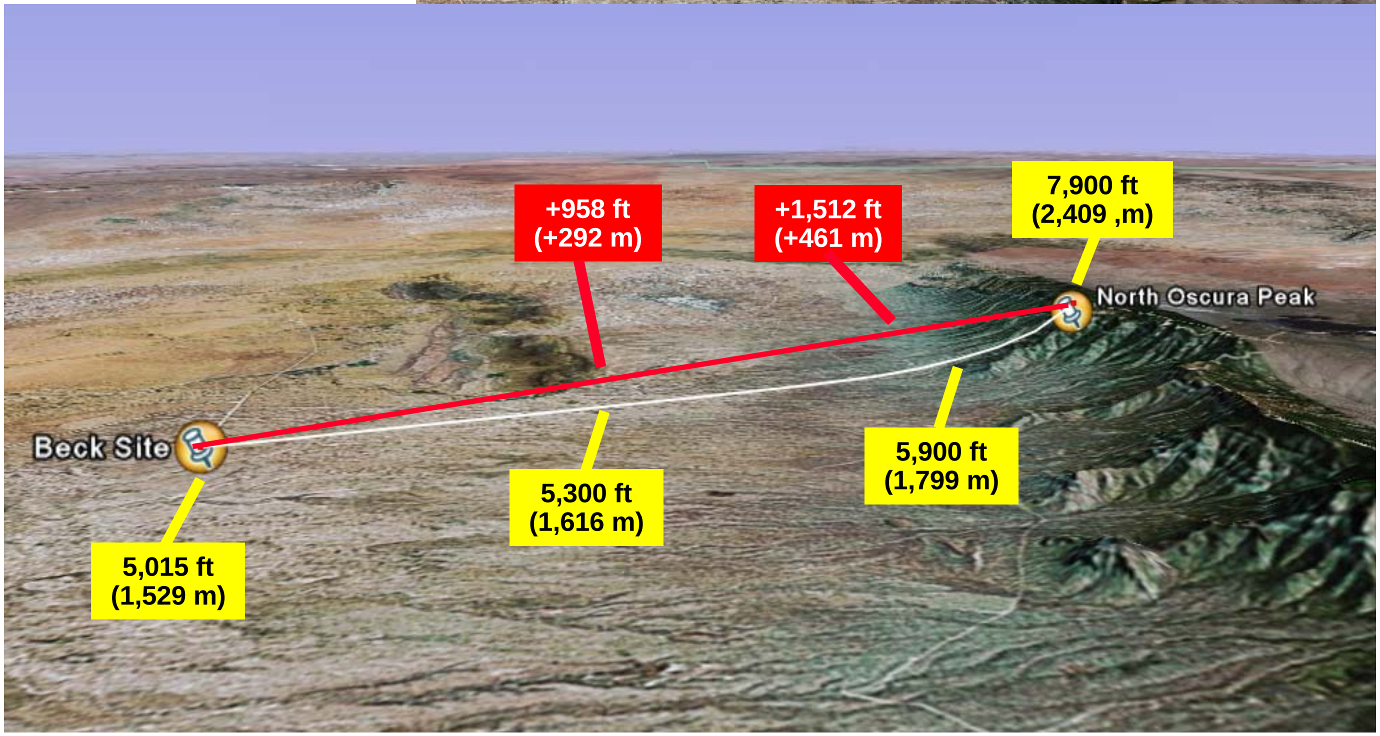


NOP-to-Beck Site Data Collection

MZA Associates Corporation

- **Turbulence profiler data was collected on NOP-to-Beck path**
  - **9.6 km, ~900 m altitude change**
  - **April-August 2006**
  - **Other data items**
    - **Scintillometer**
    - **Tactical imagery**

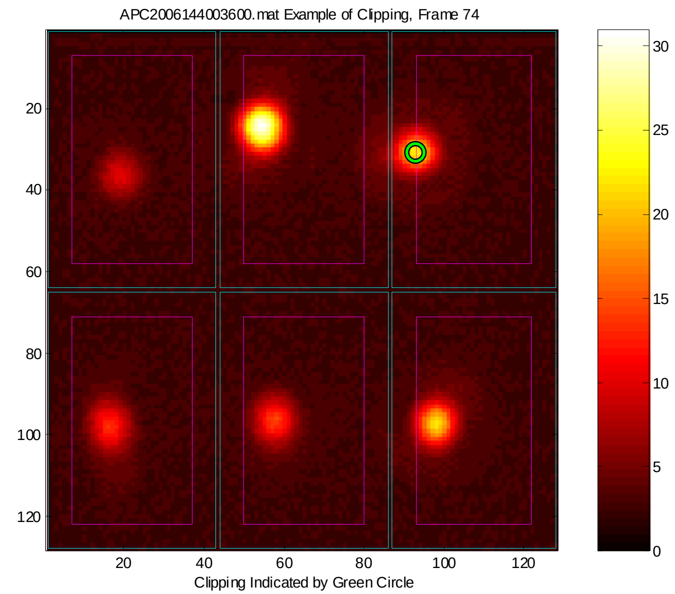
- **33 test days with profiler**
- **21 days of good quality/volume for profiling**
- **~4500 data files**
- **726 profiles**
  - **0000-0600: 120**
  - **0600-1200: 86**
  - **1200-1800: 110**
  - **1800-2400: 410**



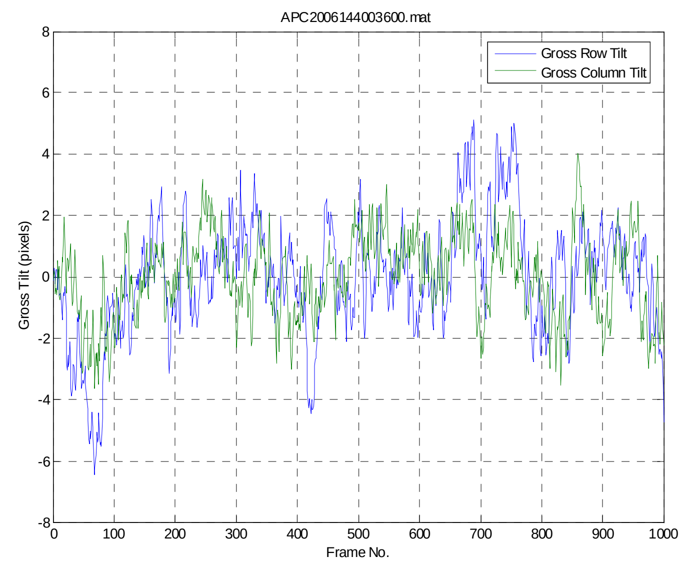
MZA Associates Corporation

Data Quality Checking

- **Data filtering implemented to reduce noise sources in differential-tilt estimation**
- **Spot SNR**
  - **Average pixel SNR $\geq$ 2 for all subapertures**
- **Saturated spot image**
  - **No saturated pixels used in centroid**
- **Spot clipping**
  - **Subaperture spot too close to centroid processing boundary**
- **Telescope jitter**
  - **Quantified by averaging shift over all subapertures**
  - **Retained data with jitter std < 7 pixels**
- **Required following attributes for profile processing**
  - **At least 10% of frames in a file must pass all quality checks**
  - **At least 200 frames total passing quality checks**
- **SNR was most common reason for data filtering**
  - **Especially when scintillation was high**



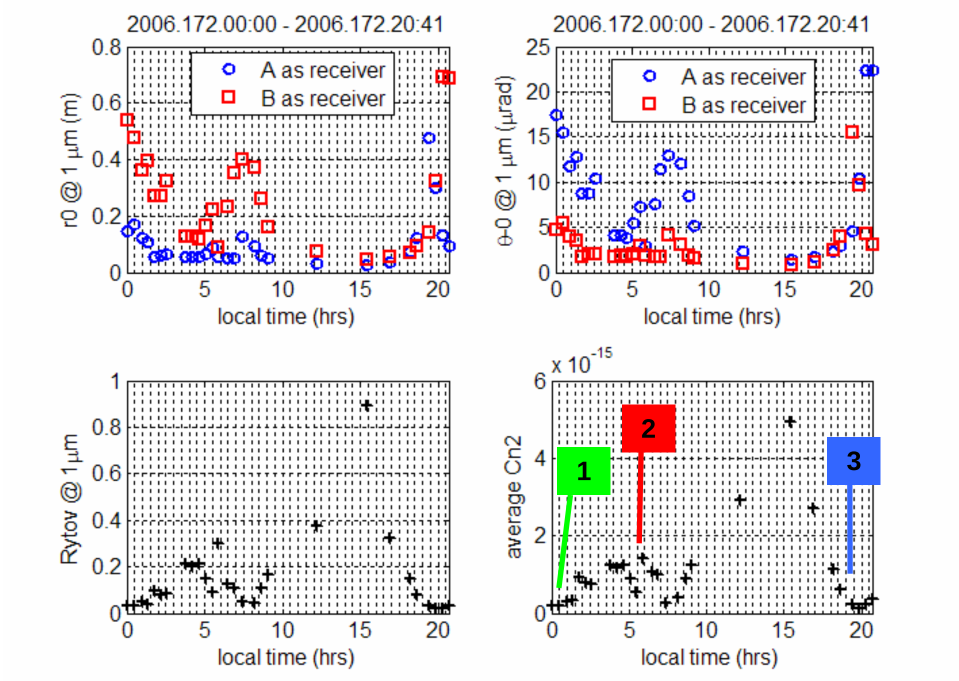
clipping

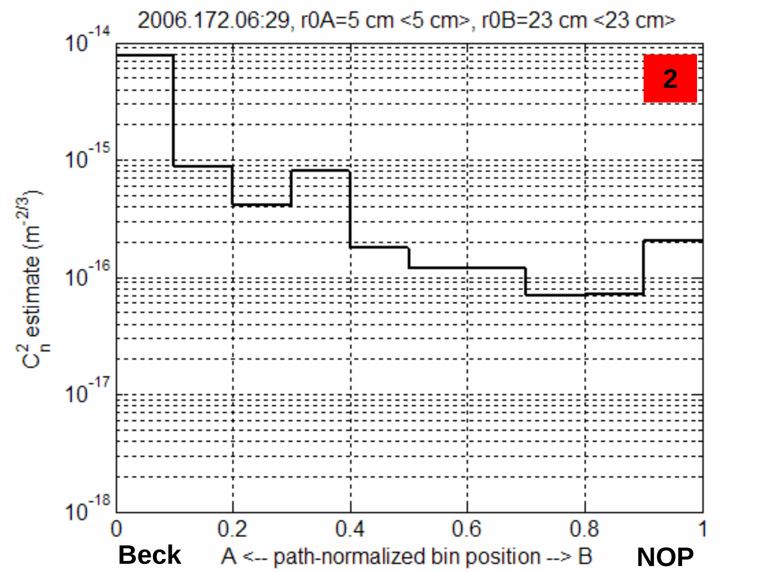


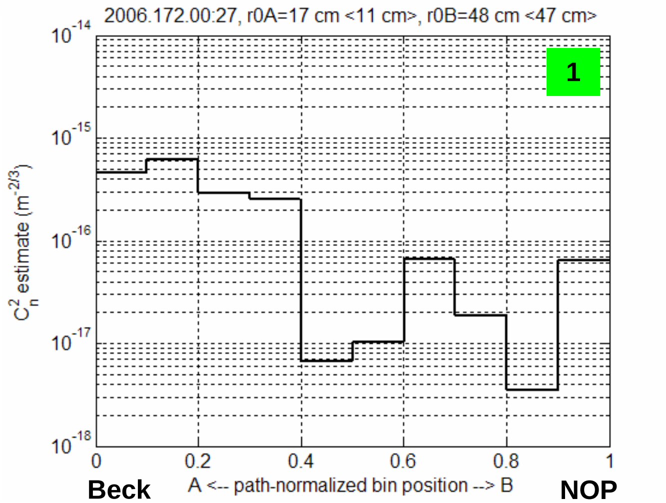
telescope jitter

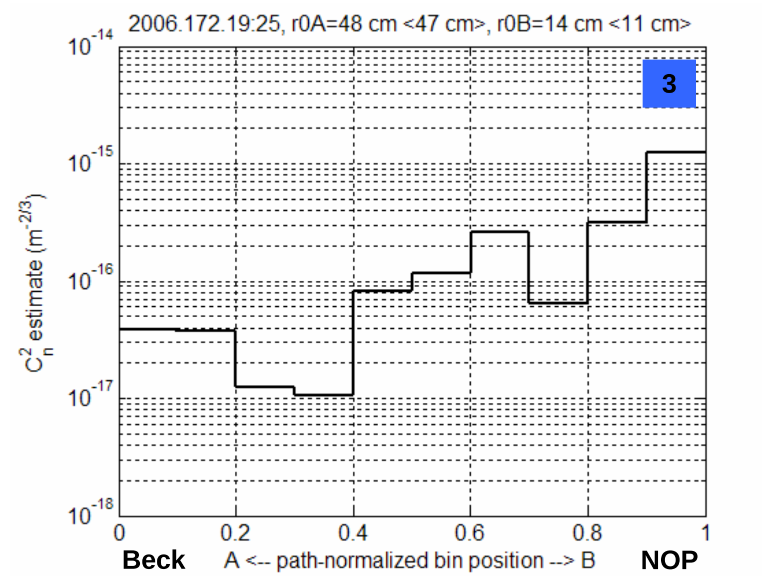
MZA Associates Corporation

Profiling Example: Day 172



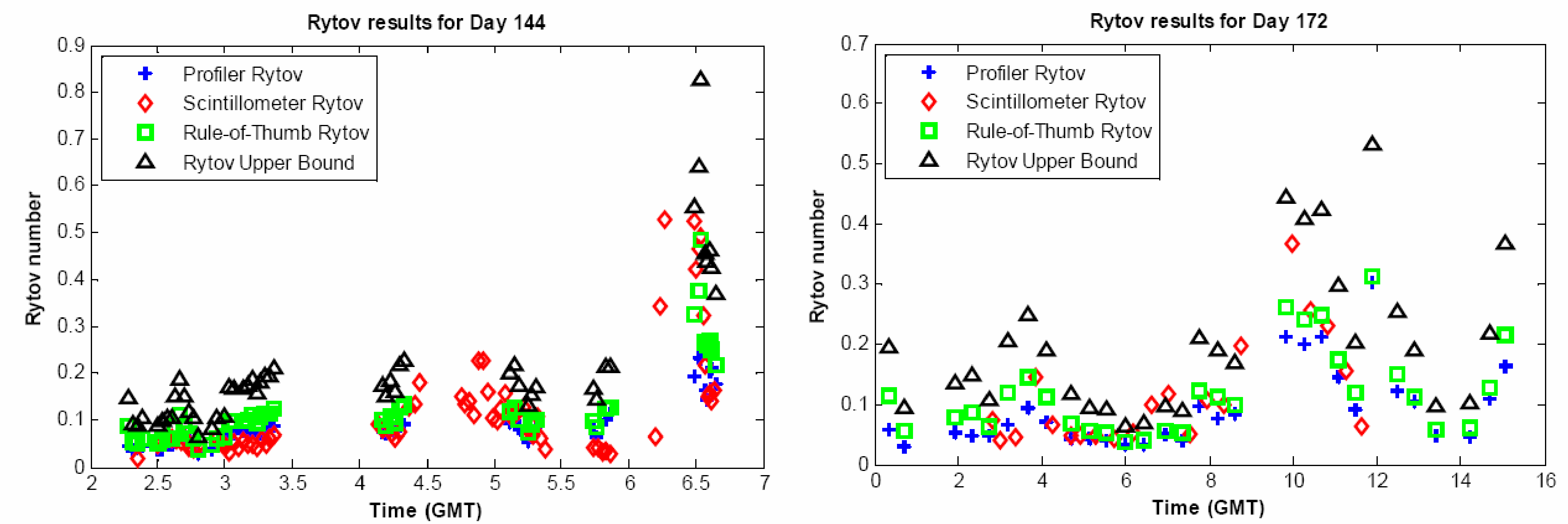






Comparison with Scintillometer

MZA Associates Corporation



- **Rytov number from turbulence profiles compared with scintillometer estimate of Rytov number (when available)**
- **It can be shown that for any turbulence profile, the following inequality applies:**

$$\mathcal{R} \leq \frac{1}{9.1314}\left(\frac{\lambda}{r_0\theta_0}\right)^{5/6}$$

- **A good "rule of thumb" approximation is:**

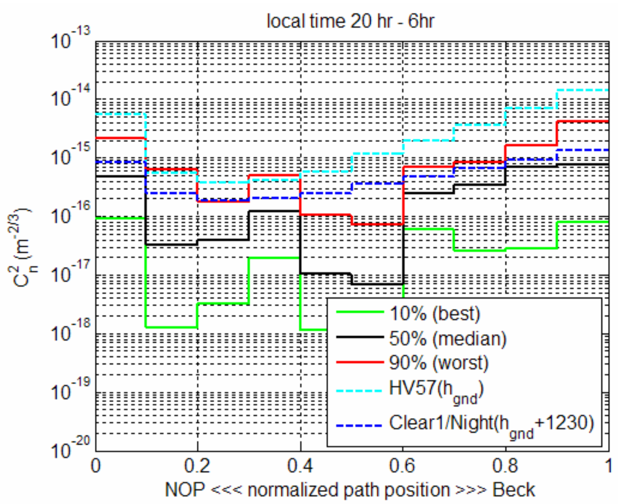
$$\mathcal{R} \simeq 15.53^{-1}\left(\frac{\lambda}{r_0\theta_0}\right)^{5/6}$$

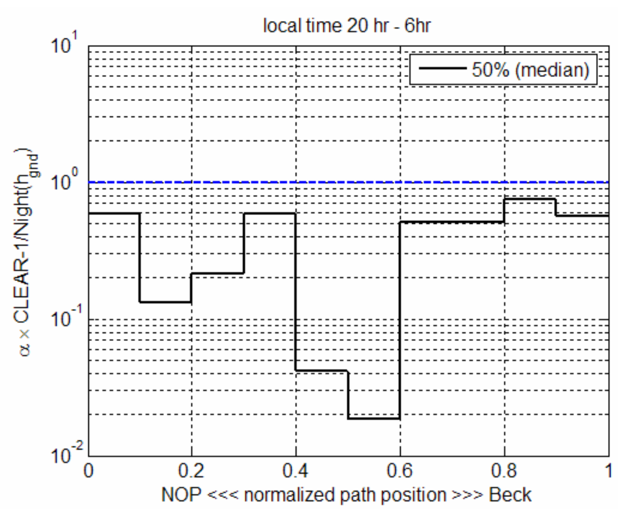
- **When scintillometer is in bounds implied by profiler, scintillometer and profiler give consistent Rytov number estimates**

MZA Associates Corporation

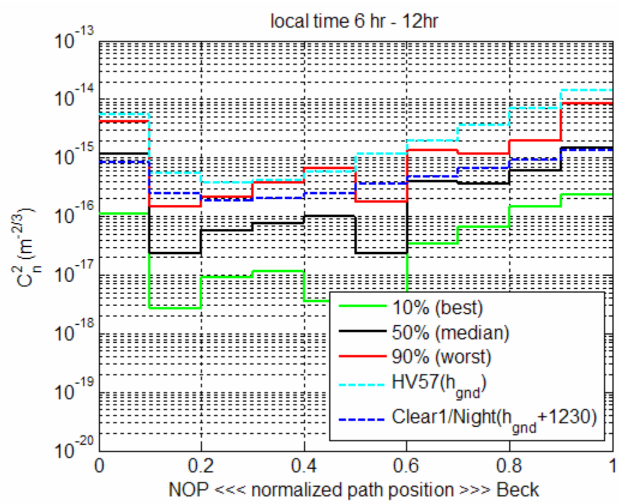
Comparison with Standard Turbulence Models

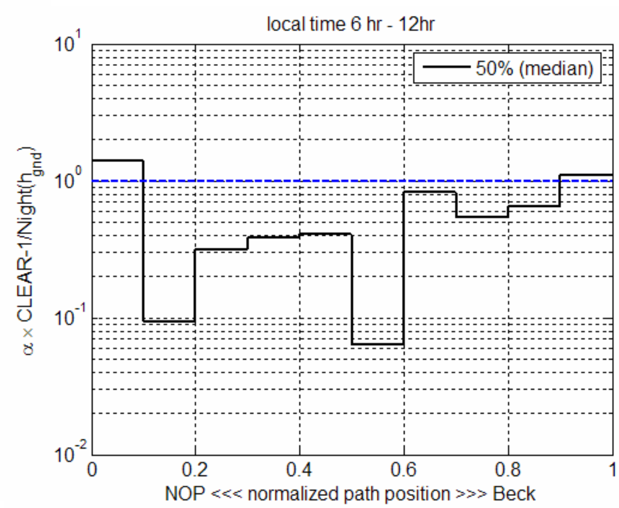
"Night" 20:00-06:00



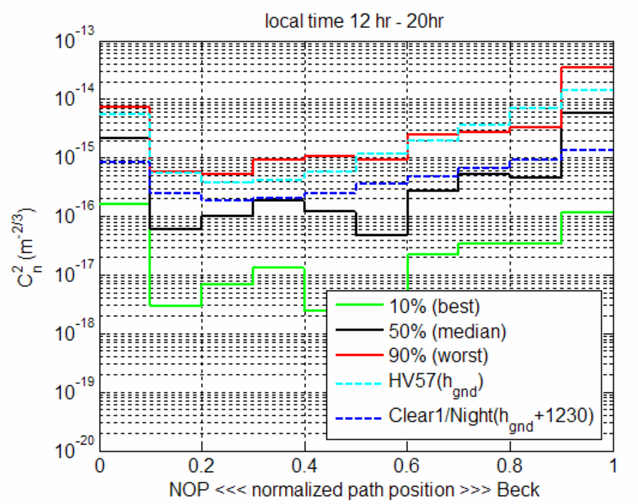


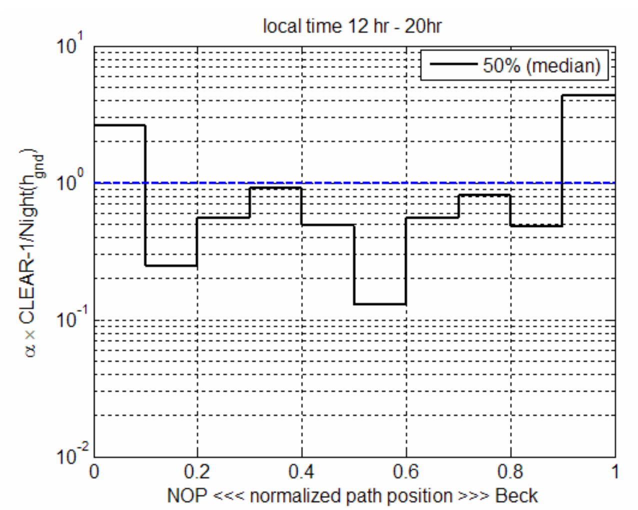
"Morning" 06:00-12:00





"Afternoon" 12:00-20:00





Conclusions

- Differential-tilt turbulence profiler successfully taken from concept to development and into application
  - ~10 km path from North Oscura Peak to valley floor at WSMR
- Substantial test data has been collected and analyzed
  - Filtering for data quality important to assuring turbulence estimate
  - Profile estimates available around the clock
  - Profiles and derived atmospheric propagation parameters consistent with expected trends
- Profile estimates validated using independent measurements
  - Consistency between profile Rytov and scintillometer
- Diurnal trends (median conditions)
  - Compare favorably to CLEAR-1 model given propagation height above ground
  - Night
    - < 0.5 x CLEAR-1/Night
  - Morning
    - 0.5 – 1.0 x CLEAR-1/Night
  - Afternoon
    - End-points (near ground) 2.0 – 4.0 x CLEAR-1/Night
    - Otherwise, 0.5 – 1.0 x CLEAR-1/Night