Optical turbulence profiling at White Sands Missile Range North Oscura Peak

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Introduction

- **AFRL Starfire Optical Range owns/operates a device known as the "Differential-Tilt Turbulence Profiler"**
- **<u>Development timeline</u>**
  - **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)**
- **<u>Testing timeline</u>**
  - **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**

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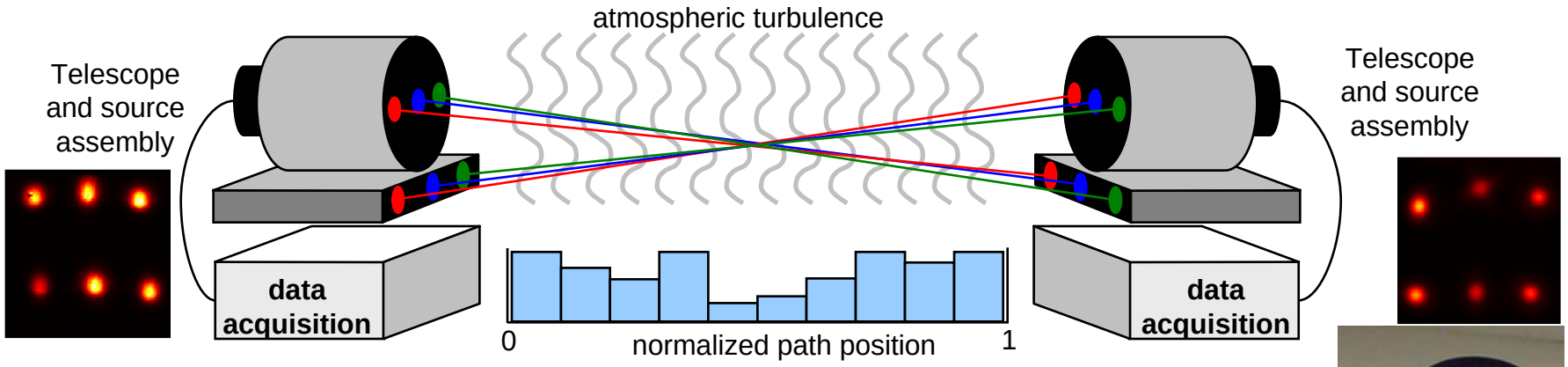
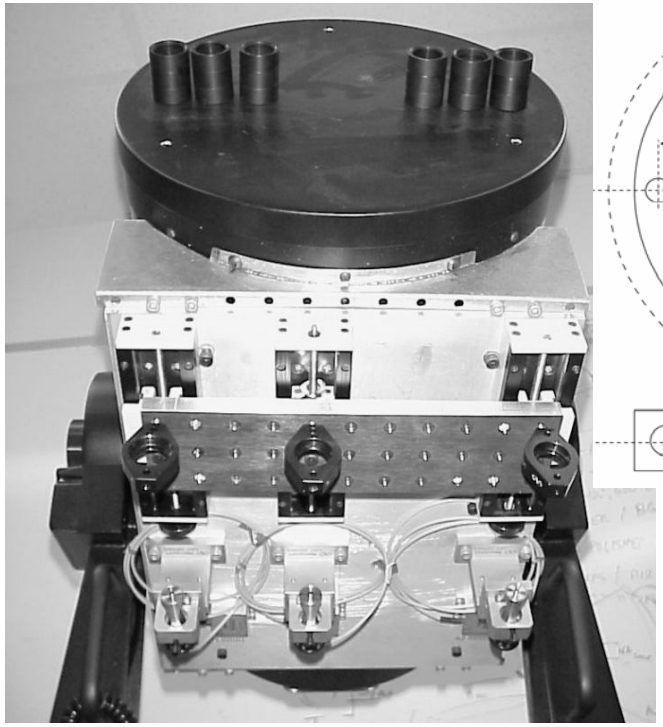
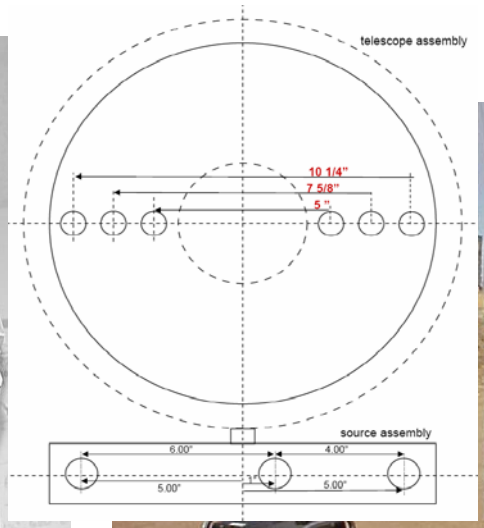
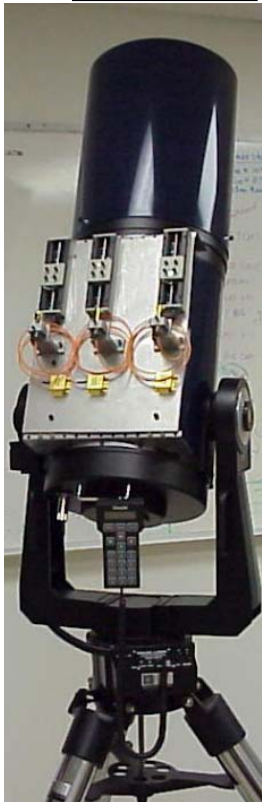
Differential-Tilt Turbulence Profiler









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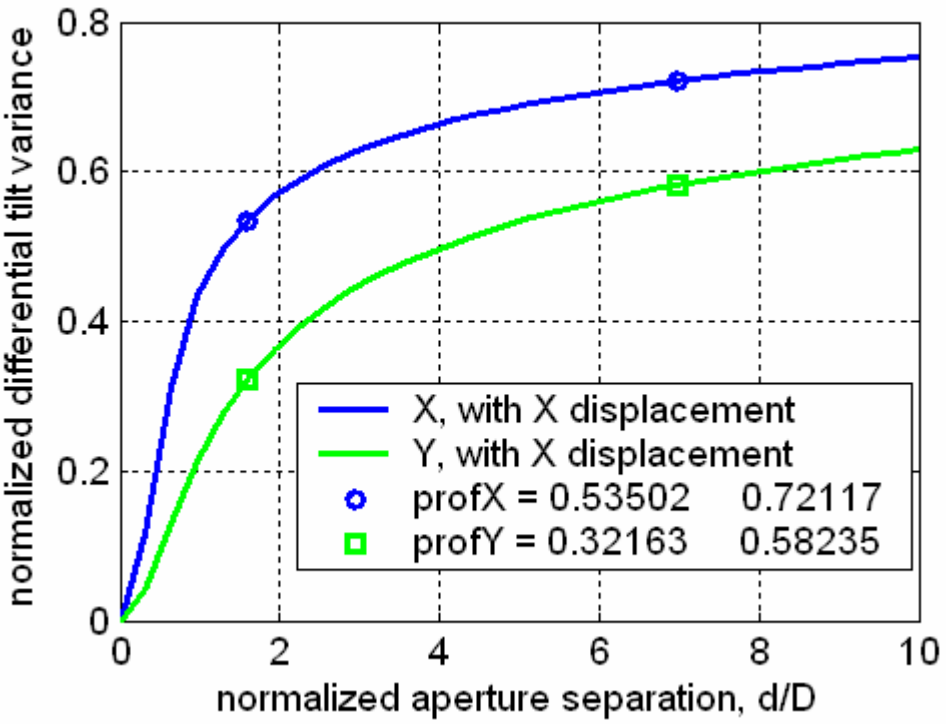
Estimation of Coherence Diameter from Profiler Centroid Data



- **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 →** $\sigma_{\Delta T}^2 = 0.1943 D^{-1/3} \lambda^2 r0^{-5/3}$

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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**

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

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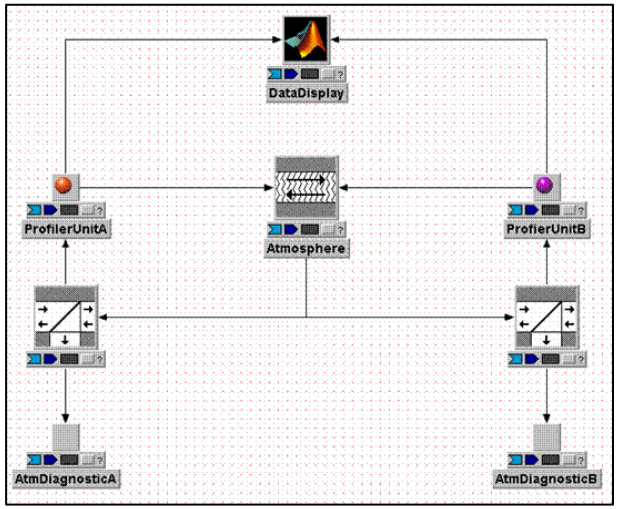
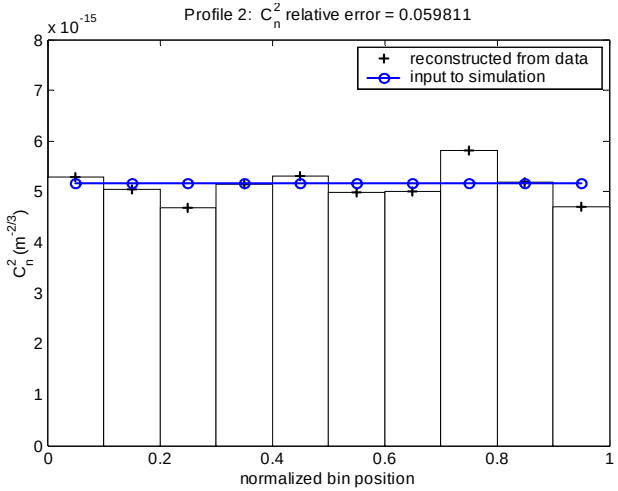
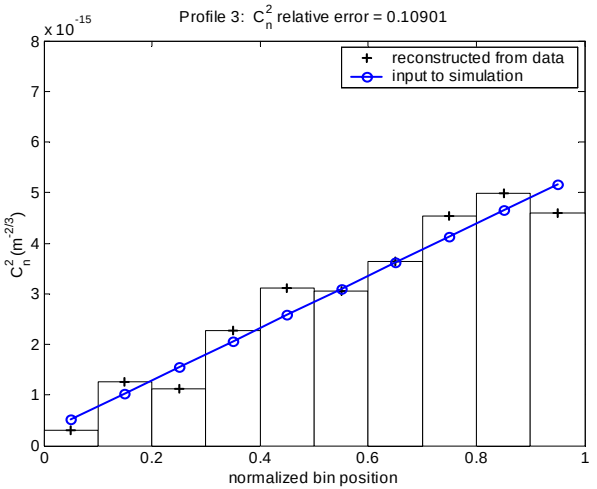
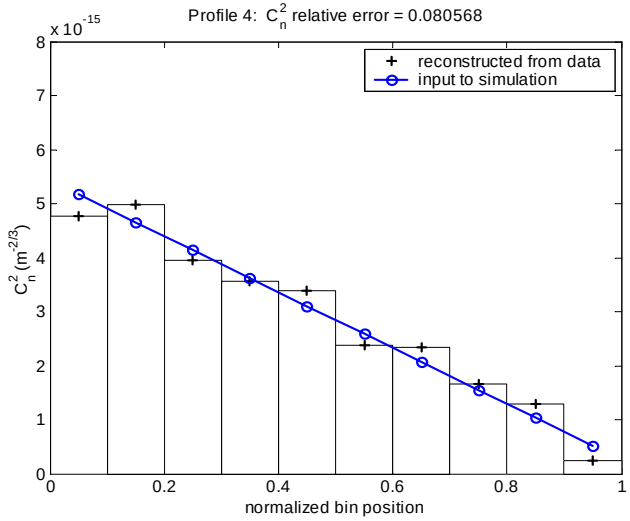
Wave-Optics Simulation of Turbulence Profiling

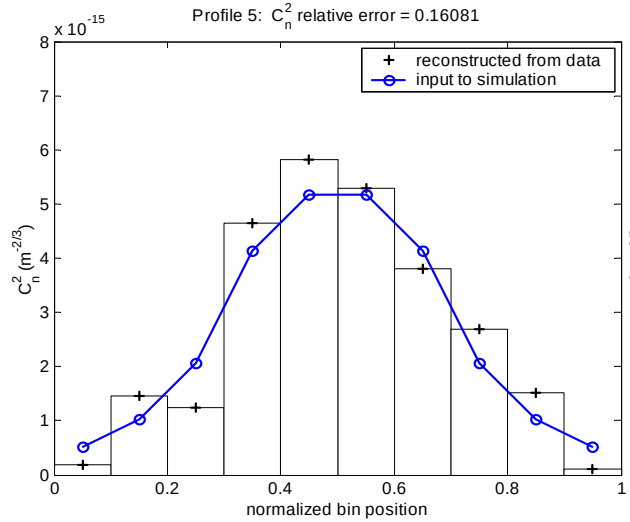
WaveTrain System Model

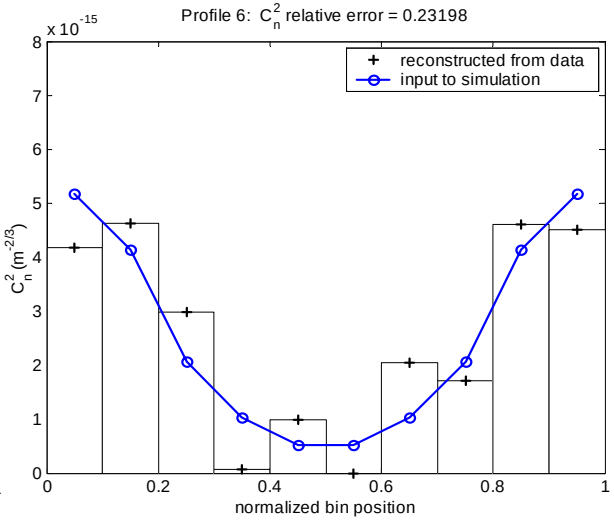












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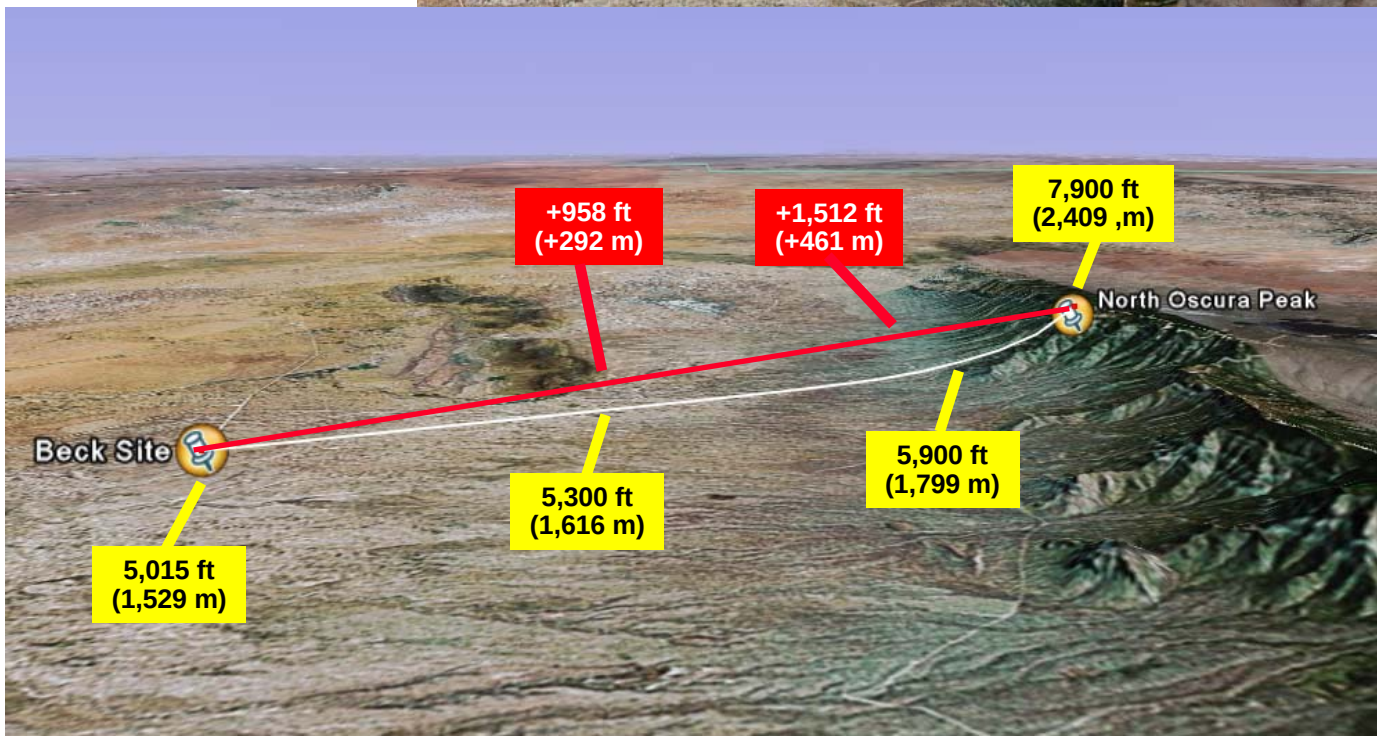
NOP-to-Beck Site Data Collection

- **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



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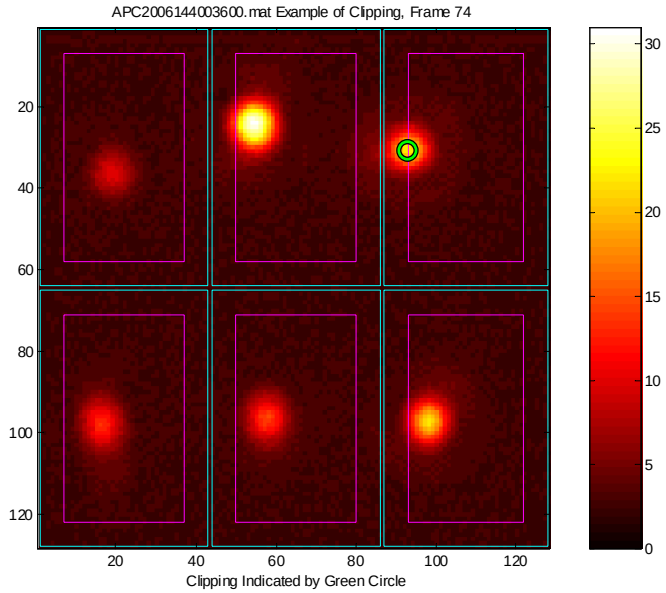
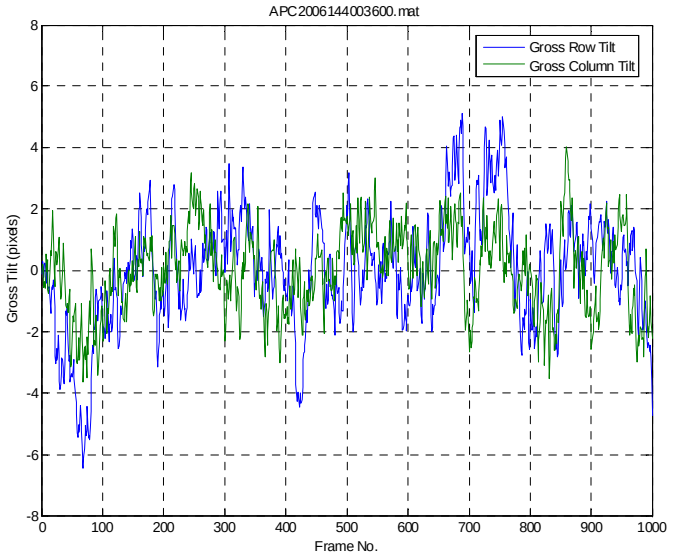
Data Quality Checking

- **Data filtering implemented to reduce noise sources in differential-tilt estimation**
- **Spot SNR**
  - **Average pixel SNR ≥ 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

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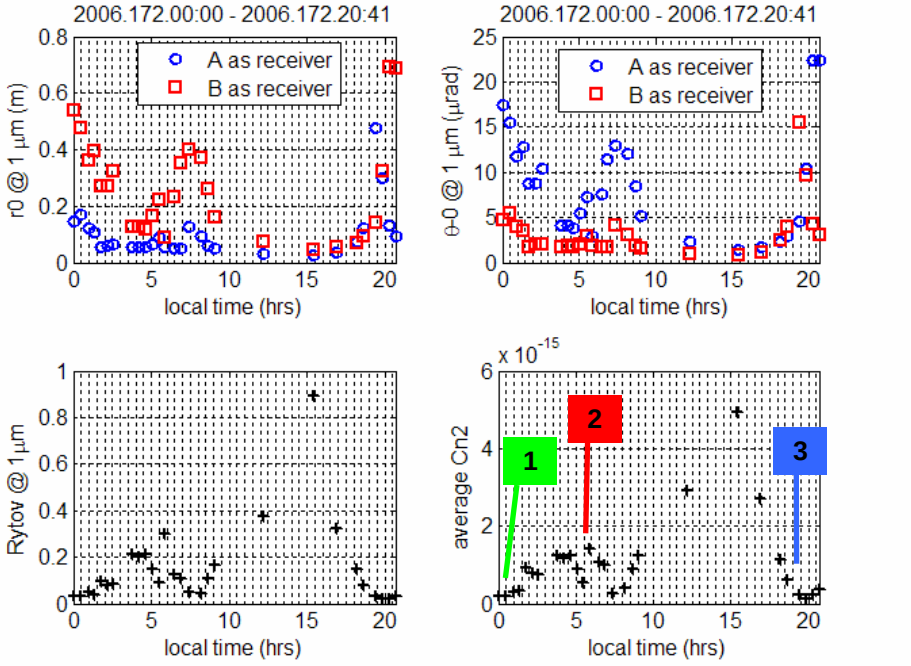
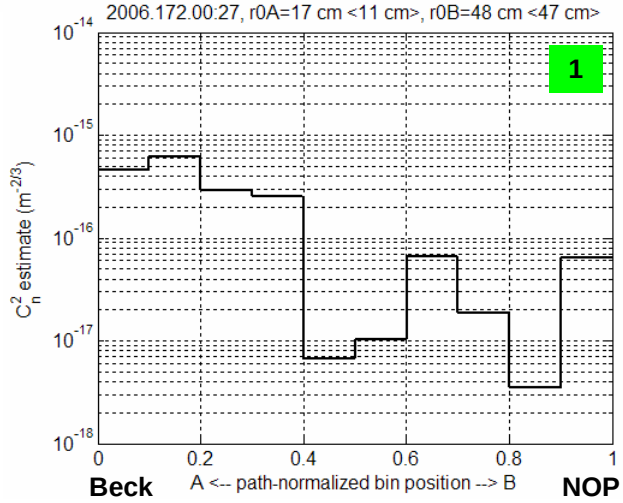
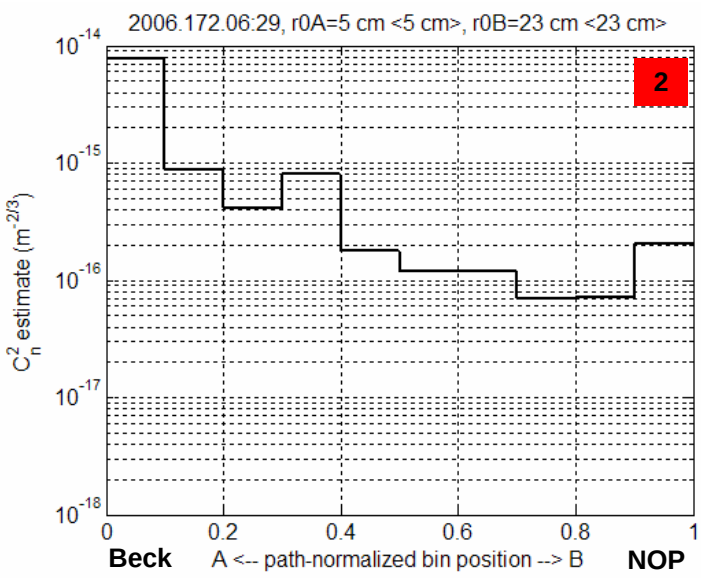
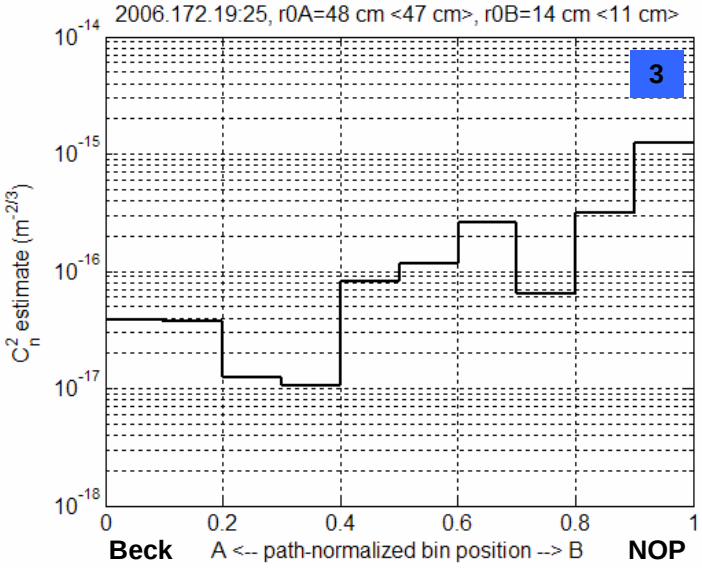
Profiling Example: Day 172









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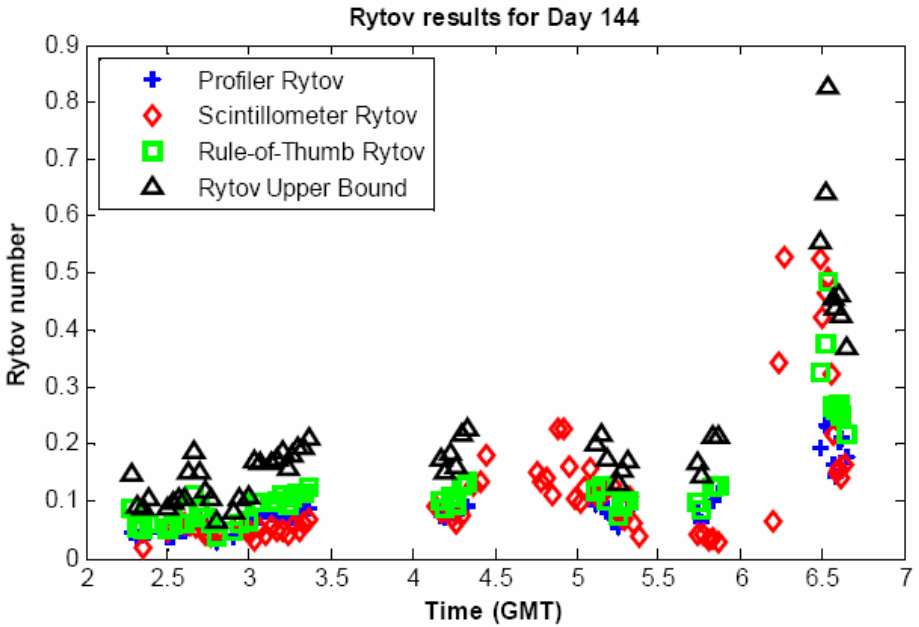
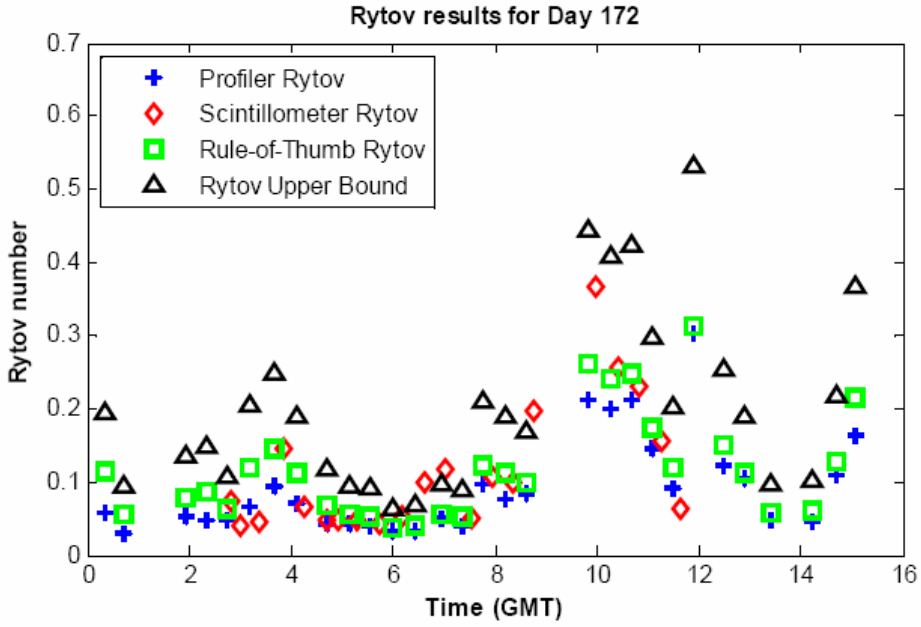
Comparison with Scintillometer





- **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**

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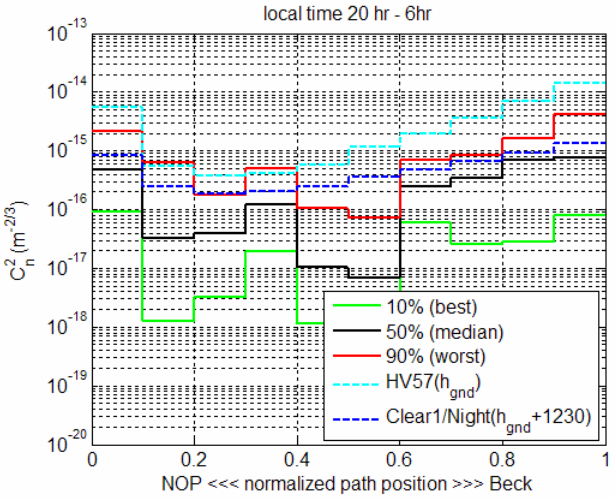
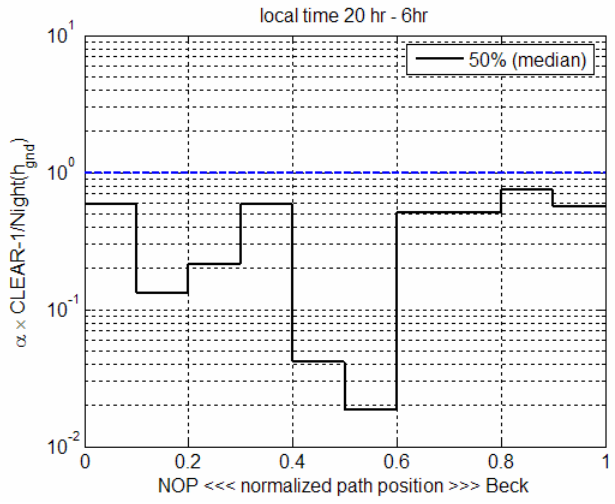
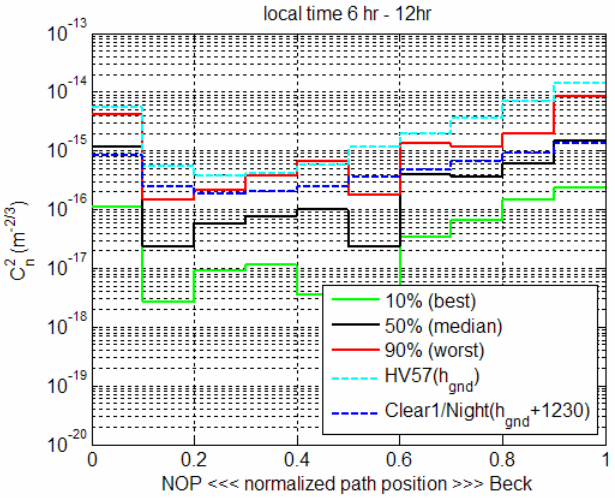
Comparison with Standard Turbulence Models

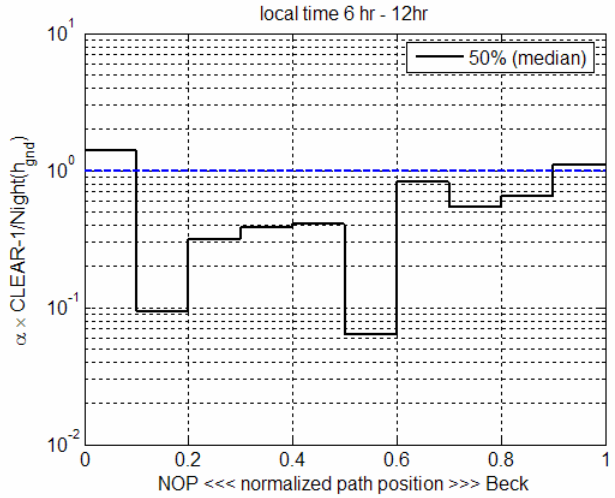
“Night” 20:00-06:00



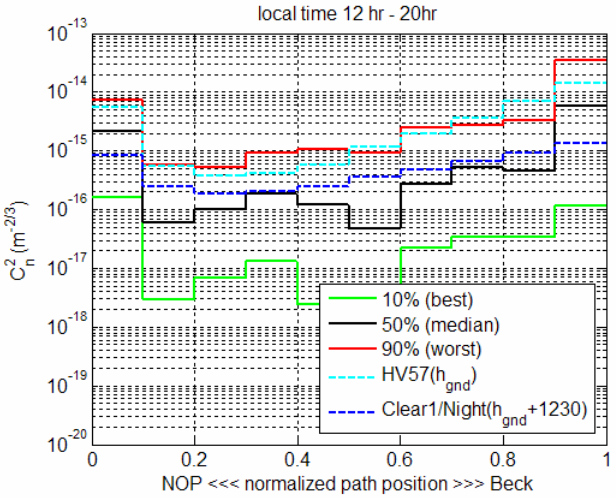


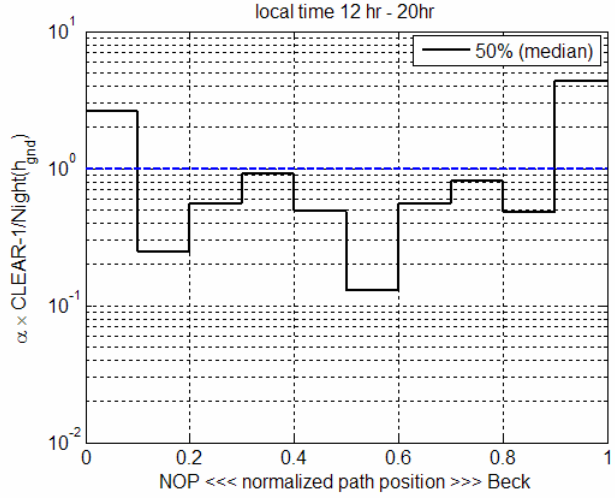
“Morning” 06:00-12:00





“Afternoon” 12:00-20:00





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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**