Optical turbulence profiling at White Sands
Missile Range North Oscura Peak

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November 2, 2006
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
Differential-Tilt Turbulence Profiler

Telescope and source assembly

Data acquisition

atmospheric turbulence

Normalized path position

Telescope and source assembly

Data acquisition

Telescope assembly

Source assembly
Can use centroid (tilt) data directly from profiler units with standard techniques for \( r_0 \) estimation

- Estimation from tilt-variance:

\[
\sigma_T^2 = 0.1816D^{-1/3}\lambda^2r_0^{-5/3}
\]

\[
r_0 = \left( \frac{\sigma_T^2D^{1/3}}{0.1816\lambda^2} \right)^{-3/5}
\]

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

- Ap-1 / Ap-2 with \( s/D = 1.5875 \) →

\[
\sigma_{\Delta T}^2 = 0.1943D^{-1/3}\lambda^2r_0^{-5/3}
\]

- Ap-3 / Ap-4 with \( s/D = 6.9850 \) →

\[
\sigma_{\Delta T}^2 = 0.2619D^{-1/3}\lambda^2r_0^{-5/3}
\]

- Ap-5 / Ap-6 with \( s/D = 1.5875 \) →

\[
\sigma_{\Delta T}^2 = 0.1943D^{-1/3}\lambda^2r_0^{-5/3}
\]
Profiler Theory of Operation

- Profiler theory published in SPIE proceedings

- Difference of differential-tilt variances define measurement set that can be related to turbulence distribution over path

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

\[
\text{discrete: } m_k = \sum_{i=1}^N C_{n_i}^2 p_{ki} \rightarrow m = Pc
\]

- 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

\[
c = (P^TP)^{-1}(P^Tm + \lambda_A w_{rA} + \lambda_B w_{rB})
\]
Wave-Optics Simulation of Turbulence Profiling

WaveTrain System Model

Profile 2: $C_n^2$ relative error = 0.059811
reconstructed from data
input to simulation

Profile 3: $C_n^2$ relative error = 0.10901
reconstructed from data
input to simulation

Profile 4: $C_n^2$ relative error = 0.080568
reconstructed from data
input to simulation

Profile 5: $C_n^2$ relative error = 0.16081
reconstructed from data
input to simulation

Profile 6: $C_n^2$ relative error = 0.23198
reconstructed from data
input to simulation
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
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
Profiling Example: Day 172
Comparison with Scintillometer

- Rylov number from turbulence profiles compared with scintillometer estimate of Rylov 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:
  \[ \mathcal{R} \approx 15.53^{-1} \left( \frac{\lambda}{r_0 \theta_0} \right)^{5/6} \]
- When scintillometer is in bounds implied by profiler, scintillometer and profiler give consistent Rylov number estimates
Comparison with Standard Turbulence Models

“Night” 20:00-06:00
“Morning” 06:00-12:00
“Afternoon” 12:00-20:00

[Graphs showing comparisons with standard turbulence models for different time periods.]
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