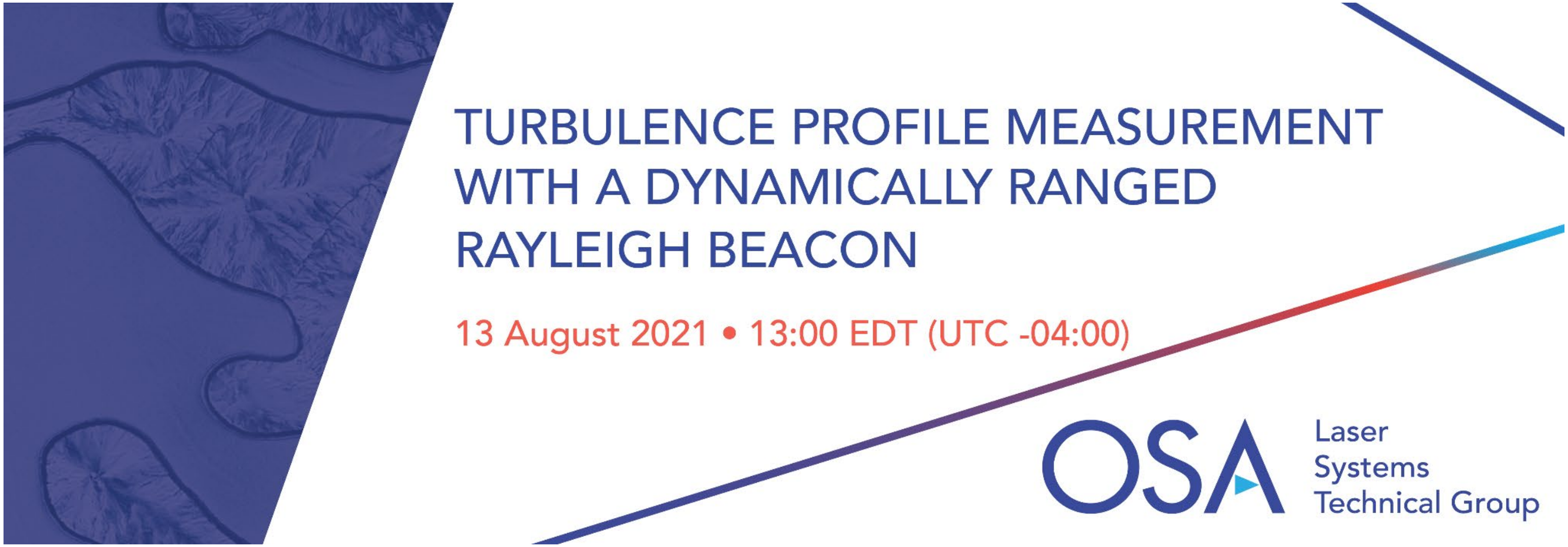
The OSA Laser Systems Technical Group Welcomes You!



TURBULENCE PROFILE MEASUREMENT WITH A DYNAMICALLY RANGED RAYLEIGH BEACON

13 August 2021 • 13:00 EDT (UTC -04:00)

OSA Laser Systems Technical Group

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OSA Laser Systems Technical Group

Technical Group at a Glance

- Focus
  - This group encompasses novel laser system development for a broad range of scientific, industrial, medical, remote sensing and other directed-energy applications.
- Mission
  - To benefit *YOU*
  - Webinars, e-Presence, publications, technical events, business events, outreach
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Today’s Webinar

Turbulence Profile Measurement with a Dynamically Ranged Rayleigh Beacon

Dr. Steven Zuraski

US Air Force Research Lab, Sensors Directorate

Speaker’s Short Bio:

Steven M. Zuraski is a researcher at the Air Force Research Labs Sensors Directorate Multi-spectral Sensing Division at Wright-Patterson AFB, Ohio. Currently, he leads the EO Space Team within the division focusing on novel sensing approaches applied to Air Force and Space Force missions for space and from space. Steven Zuraski's research interests include EO remote sensing of the environment, atmospheric turbulence characterization, passive coherent sparse aperture imaging systems, and space-based sensor systems.

Turbulence Profile Measurement with a Dynamically Ranged Rayleigh Beacon

OSA Webinar hosted by:
Laser Systems Technical Group

Steven Zuraski

AFRL Sensors Directorate

August 2021

Special Thanks to Contributors

- **Air Force Research Labs Sensors Directorate**
- **AFIT Center for Directed Energy**
- **Applied Optimization Inc.**

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LEAD | DISCOVER | DEVELOP | DELIVER

CENTER FOR DIRECTED ENERGY
RESEARCH EDUCATION INNOVATION

AO Applied Optimization

Presentation Outline

- **Research Motivation**
- **Background on Alternative Technologies**
- **Key Concepts from Theory**
- **Sensing Methodology**
- **System Prototype (TARDIS)**
- **Data Collections**
  - **Laboratory**
  - **On-Sky**
- **Next Steps**
- **Conclusion**

PC: Steven Zuraski

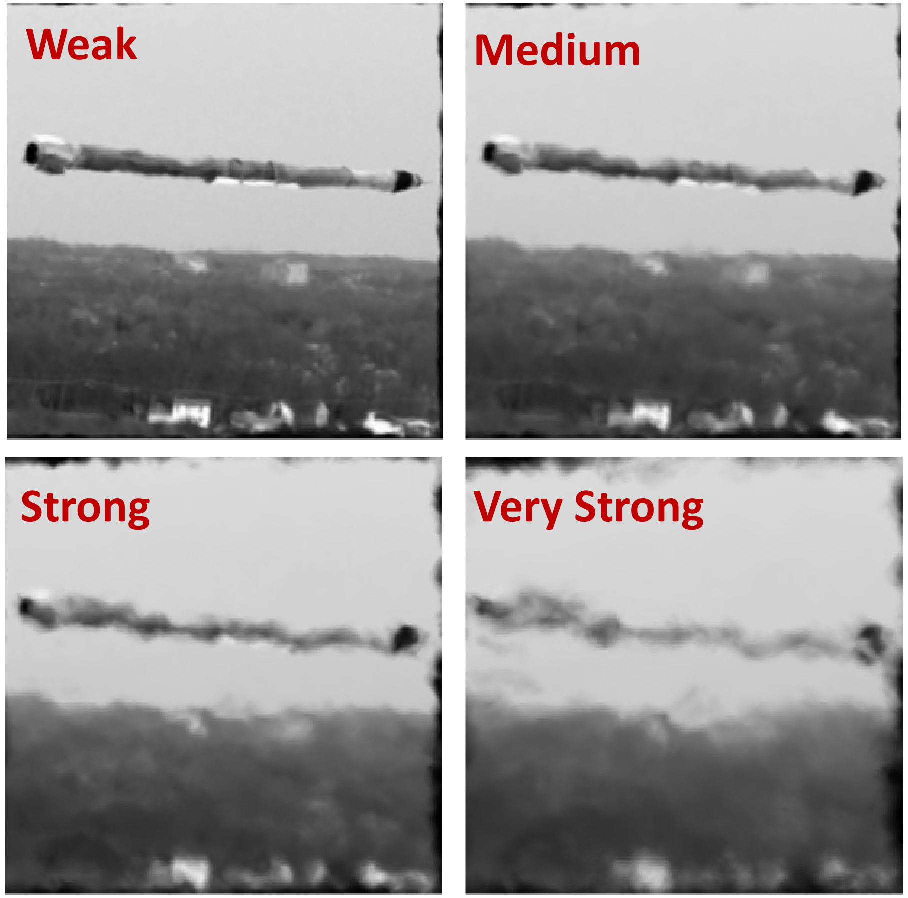
PC: Dan LeMaster

Research Motivation

- **Question:** Can the vertical structure of turbulence strength be obtained by an improved method for reliable on-demand turbulence strength profile assessments?
- **Need:** Objective measurement and characterization of the index of refraction structure constant, C_n^2
  - Current profiling measurement methods are in-situ
  - Models only provide averaged data estimates
  - Greater C_n^2 accuracy improves many next-gen turbulence mitigation strategies
  - Air Force missions impacted: laser beam propagation, free space optical communication, terrestrial imaging systems
- **Requirement:** Develop a novel turbulence profiling sensing system that can provide estimates of C_n^2 that improves upon previous methodologies

Research Motivation

Missile Images in Turbulence



S. L. Lachinova, M. A. Vorontsov, V. V. Dudorov, V. V. Kolosov, and M. T. Valley, “Anisoplanatic imaging through atmospheric turbulence: Brightness function approach,” Proc. SPIE, vol. 6708, p. 67080E, 2007.

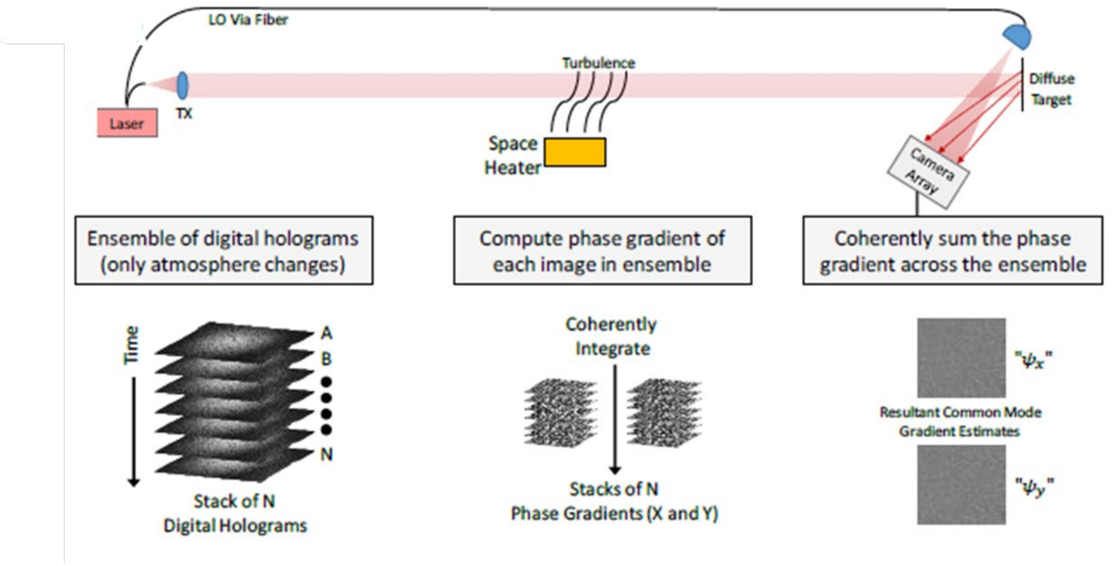
Moon Tracked through Turbulence

Movie Credit: MZA Inc.

Background on Alternative Technology: Methods for Measuring C_n^2

- Coherent LIDAR based system
  - Range resolved point features of the target
  - Estimation of wave structure function, $D(r)$
  - $D(r)$ is fit to r_0 and C_n^2
  - Horizontal path measurements performed by Montana State University
- Dynamic refocus system: University of Arizona
  - Applied to Multi-Mirror Telescope and Giant Magellan telescope
  - Allows for more photons to be sensed for ranges 20km to 30km
  - Supports multi-laser beacon research
  - For MMT: focal shifts of 113 microns are expected
- Integrated volume measurements (r_0)
  - Fixed range guide stars (natural, Rayleigh, and sodium)

Coherent LIDAR

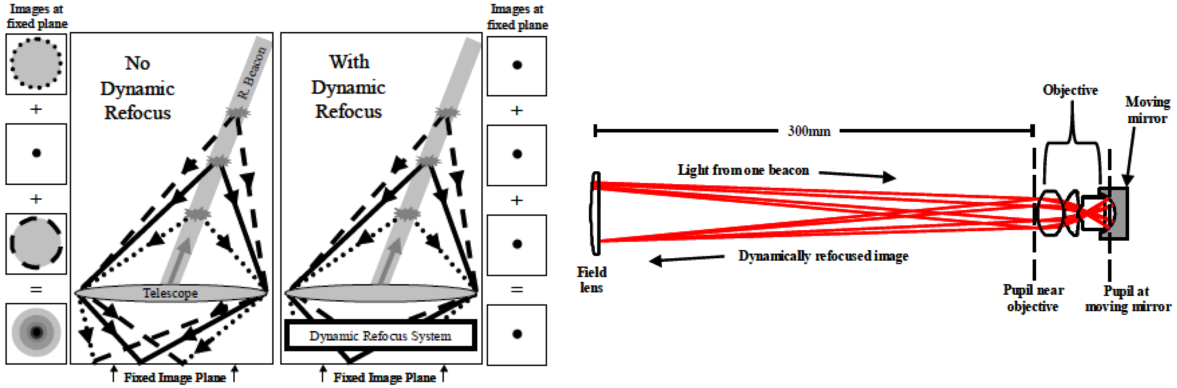


Ensemble of digital holograms (only atmosphere changes)

Compute phase gradient of each image in ensemble

Coherently sum the phase gradient across the ensemble

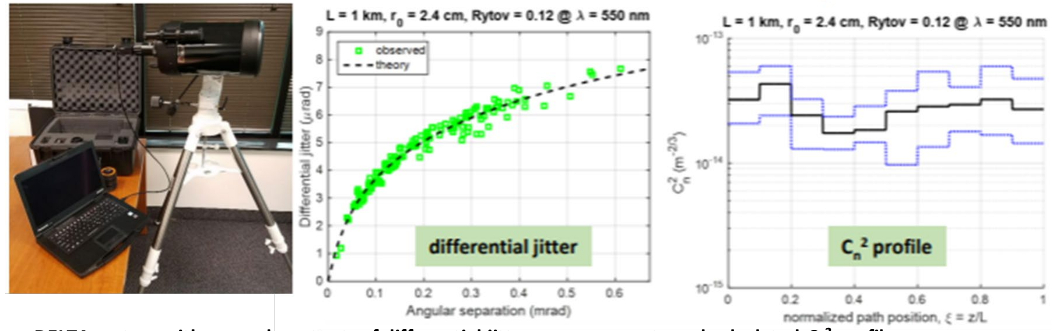
Dynamic Refocus System



Background on Alternative Technology: Methods for Inferring C_n^2

- Balloon born and satellite sounding based in situ measurements of weather parameters
- Slope Detection and Ranging (SLODAR)
- Imaging shadow patterns in scintillation
  - Scintillation Detection and Ranging (SCIDAR)
  - Multi-Aperture Scintillation Sensor (MASS)
- Wind profiling LiDARs
- Differential Image Motion (DIM)
- Acoustic sounding radar based measurements

DIM Method:



DELTA system with example outputs of differential jitter measurements and calculated C_n^2 profiles

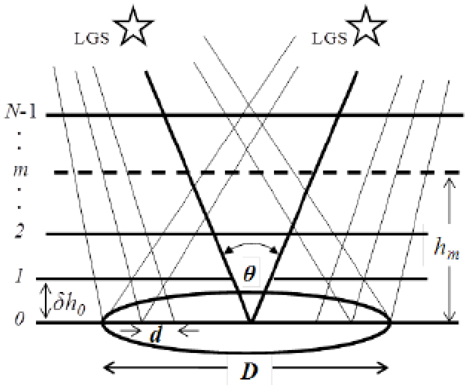
Weather Parameter Method:

$$C_N^2 = \left(7.9 \times 10^{-5} \frac{P}{T^2}\right)^2 C_T^2$$

SLODAR Method:

$$\sigma_d^2 = .179\lambda^2 r_0^{-\frac{5}{3}} d^{-\frac{1}{3}}$$

$$r_0 = \left[.423k^2 sec\xi \int_0^H C_n^2(z)dz\right]^{-\frac{3}{5}}$$



Geometry for a SLODAR System

MASS Method:

$$s_k^2 = \int W_k(z)C_n^2(z)dz$$

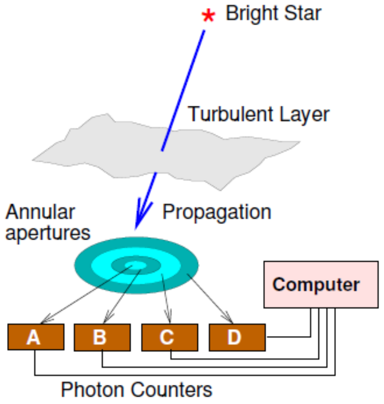
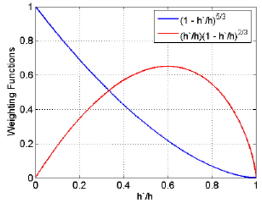


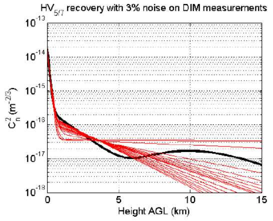
Fig. 08. Principle for a MASS

DIM LiDAR Method:

$$\sigma_{DIM}^2 = f(d/D)D^{-1/3}\bar{C}_n^2$$



Weighting Functions



C_n^2 profile from data

Background on Alternative Technology: Methods for Modeling C_n^2

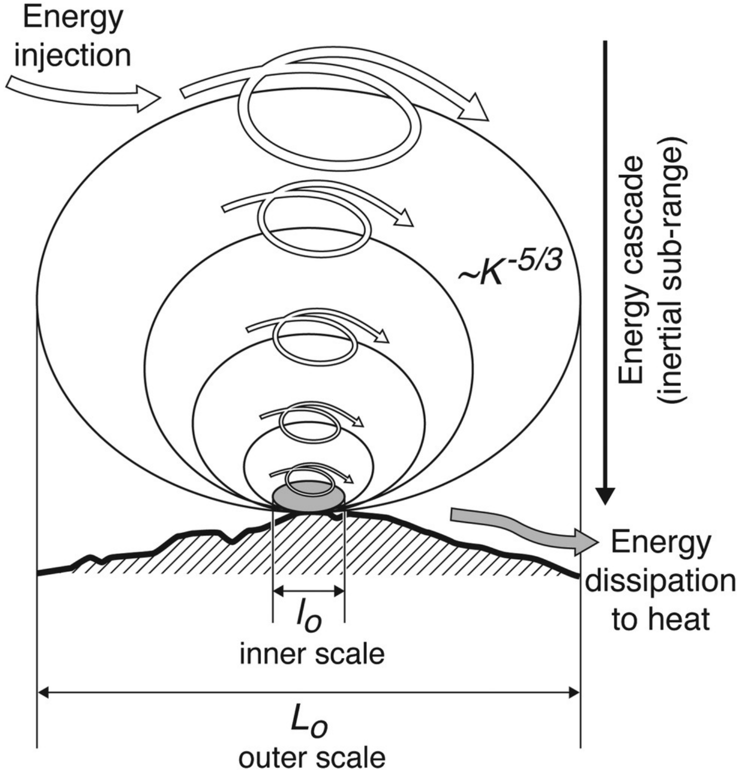
- Dimensional analysis within the inertial subrange (between inner and outer scales): Kolmogorov's power law; locally homogeneous and isotropic
- Tatarski based relations: $C_n^2 = 2.8\frac{K_H}{K_M}\left(79\times 10^{-6}\frac{P}{T^2}\right)^2 L_0^{\frac{4}{3}}\left(\frac{dT}{dz}+\gamma_d\right)^2$

  and $C_T^2 = 2.8\frac{K_H}{K_M}L_0^{\frac{4}{3}}\left(\frac{dT}{dz}+\gamma_d\right)^2$ where $\frac{K_H}{K_M} = \begin{cases} \frac{1}{7R_i} & for\ R_i \geq 1 \\ \frac{1}{6.879R_i+\frac{1}{1+6.873R_i}} & for\ 0.01 < R_i \leq 1 \end{cases}$
- Fitted models to match data:

$$C_n^2(h) = A\left[2.2\times 10^{-53}h^{10}\left(\frac{w}{27}\right)^2 exp\left(-\frac{h}{1000}\right) + 1\times 10^{-16}exp\left(-\frac{h}{1500}\right)\right] + Bexp\left(-\frac{h}{100}\right)$$

$$C_N^2(h) = Aexp\left(-\frac{h}{H_A}\right) + Bexp\left(-\frac{h}{H_B}\right) + Ch^{10}exp\left(-\frac{h}{H_C}\right) + Dexp\left(-\frac{(h-H_D)^2}{2d^2}\right)$$

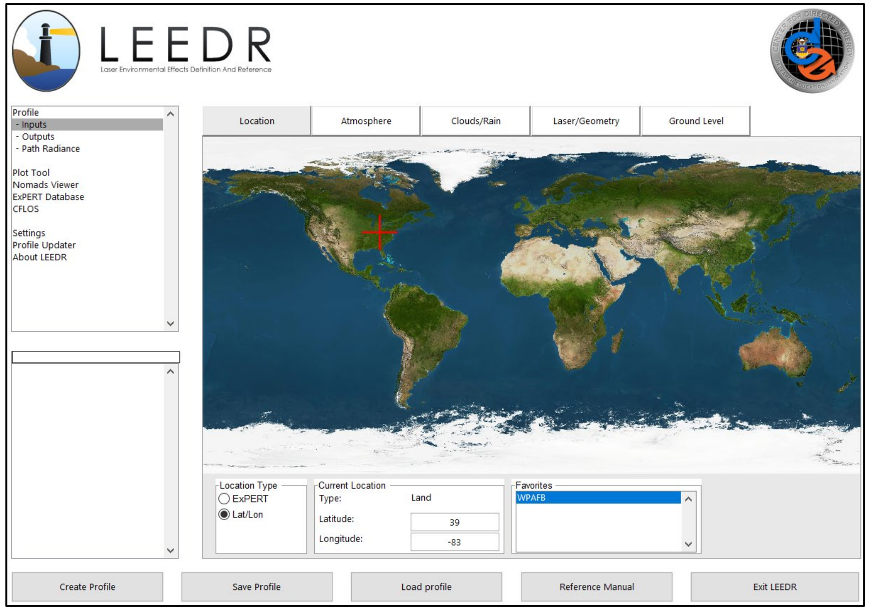
A for boundary layer region, *B* for troposphere, *C* for tropopause, and *D* for isolated layers



T. Cherubini and S. Businger. " Another Look at the Refractive Index Structure Function". *Journal of Applied Meteorology and Climatology* 52.2 (2013): 498-506.

Background on Alternative Technology: LEEDR

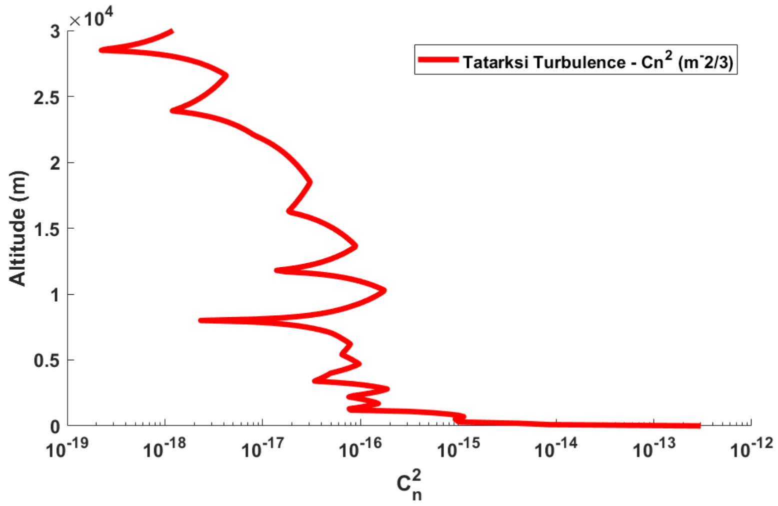
- Laser Environmental Effects Definition and Reference
- Atmospheric characterization and radiative transfer code developed and maintained by AFIT Center for Directed Energy
- Creates physically realizable, correlated, vertical profiles of meteorological and weather event data for any worldwide location
- Incorporates climatological databases and numerical weather prediction (NWP) model data, primarily Global Forecast System (GFS), and surface observations to improve accuracy of model
- Generates vertical profiles of optical turbulence using Tatarski calculations based on observed and modeled atmospheric conditions
    - Allows for turbulence predictions and analysis



Location Type
○ ExPERT
● Lat/Lon

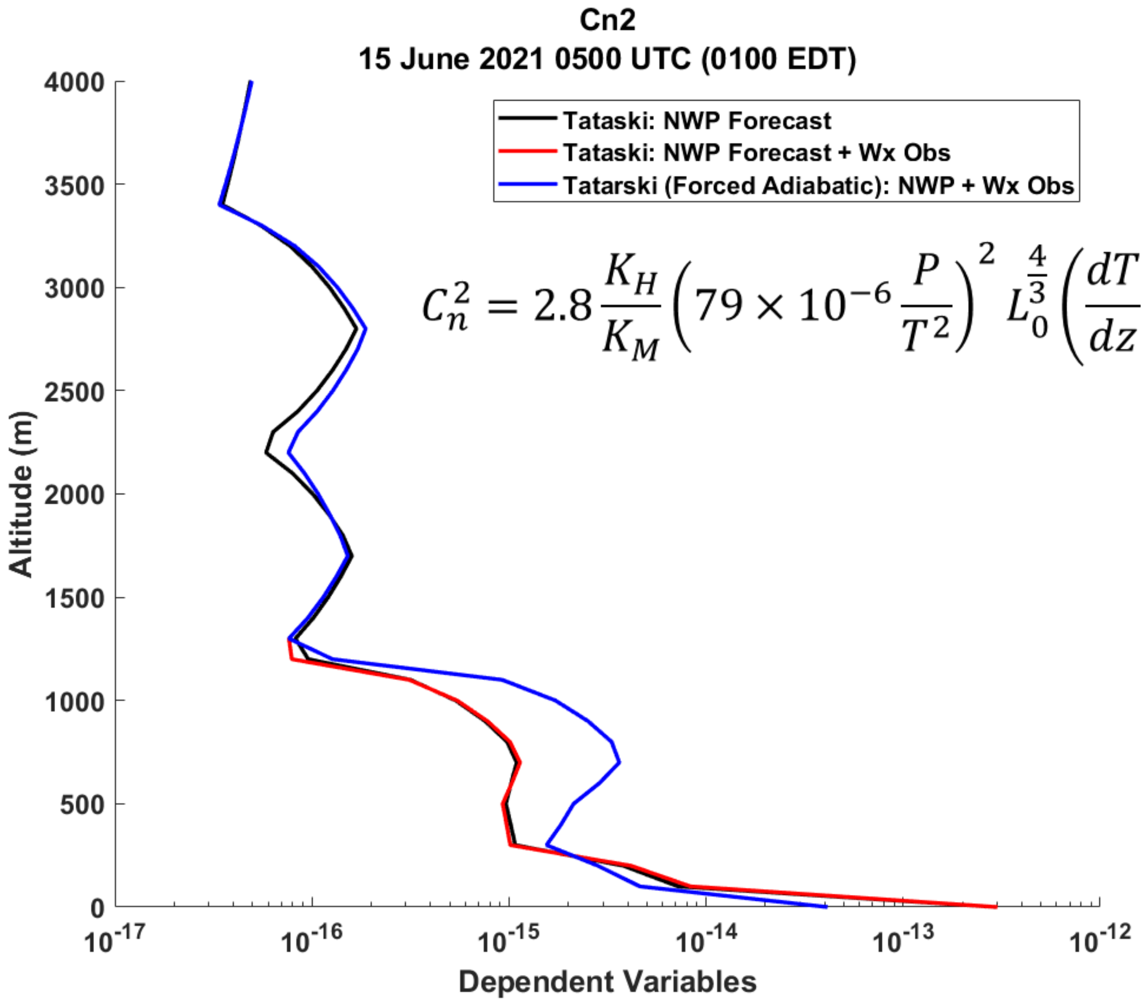
Current Location
Type: Land
Latitude: 39
Longitude: -83

Favorites
WPAFB



Background on Alternative Technology: LEEDR

- **Tatarski, NWP Forecast**: Based on NWP meteorological variables (e.g. T, P) to generate C_n^2 profiles.
- **Tatarski, NWP + Weather Obs**: C_n^2 profiles based on (1) observed surface conditions and assuming an adiabatic lapse rate to the top of the boundary layer and then (2) reverting to NWP data above the boundary layer.
- **Tatarski – Forced Adiabatic**: This option makes a linear interpolation of temperature based on observed surface conditions from the surface to the boundary layer to remove an abnormal temperature gradient at the boundary layer.



$$C_n^2 = 2.8\frac{K_H}{K_M}\left(79\times 10^{-6}\frac{P}{T^2}\right)^2 L_0^{\frac{4}{3}}\left(\frac{dT}{dz}+\gamma_d\right)^2$$

Key Concepts from Theory

- Three basic phenomenon that affect optical wave propagation:
  1. Absorption: gives rise to the attenuation of the optical wave
  2. **Scattering**: basis for returned laser energy from a Rayleigh beacon
  3. **Refractive-index fluctuations**: give rise to wavefront distortions
- Atmospheric coherence width, r_0: measure of an effective aperture of an imaging system
  - Related to spatial coherence radius, $r_0 = 2.1\rho_0$
  - $r_0 = \left[0.423 sec(\xi) k^2 \int_{h_0}^{H} C_n^2(h) dh\right]^{-3/5}$
- Greenwood frequency: characteristic frequency of atmospheric turbulence
  - Determined by wind velocity and turbulence for a static viewing scenario
  - $f_G = \left[0.102 k^2 (sec\zeta) \int_0^{\infty} C_n^2(h) v^{\frac{5}{3}}(h) dh\right]^{\frac{3}{5}}$

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    - **Laboratory**
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- **Next Steps**
- **Conclusion**

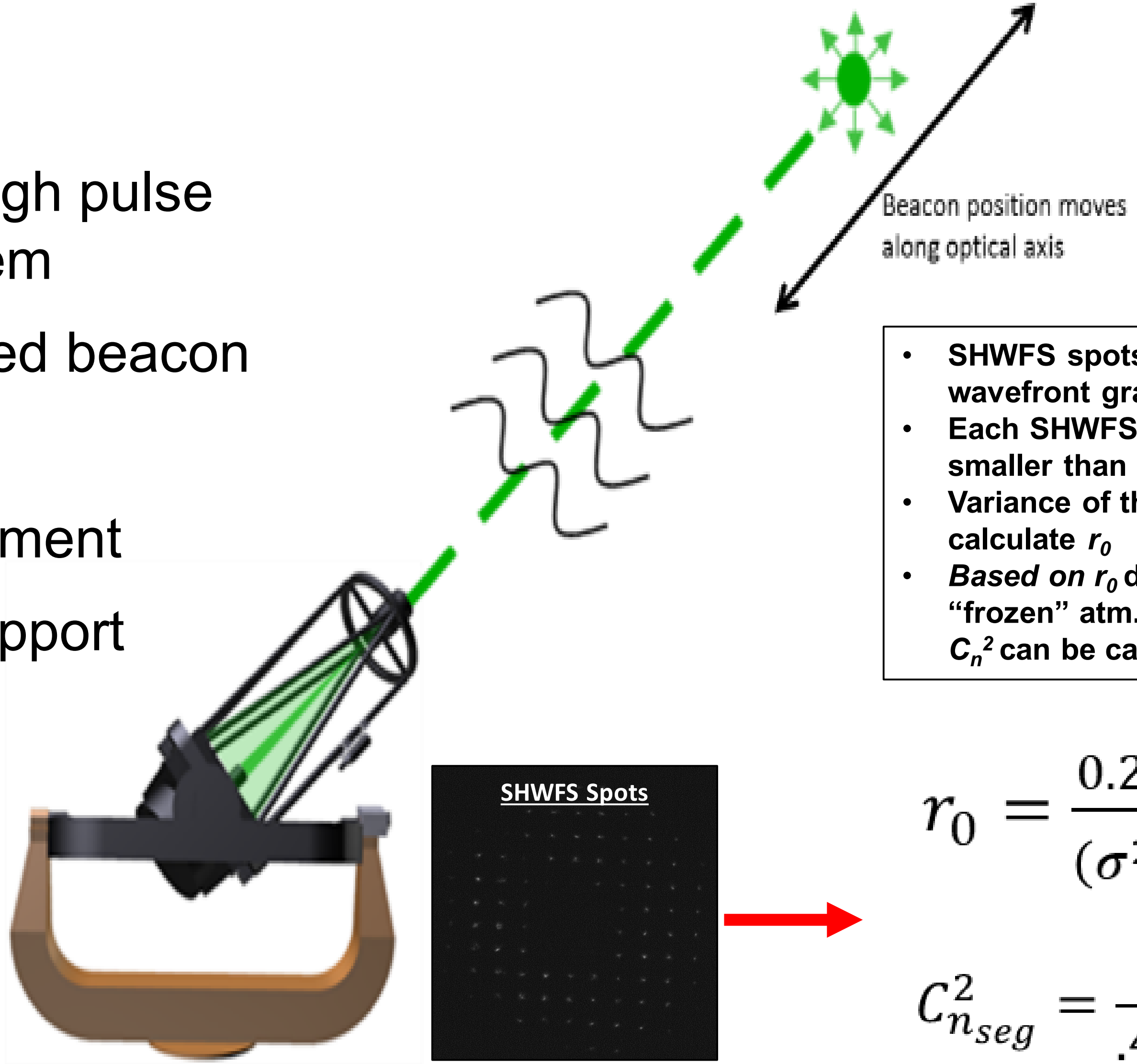
PC: Steven Zuraski

PC: Dan LeMaster

Sensing Methodology: Dynamically Ranged Rayleigh Beacon

Main System Qualities

- High repetition rate and high pulse energy density laser system
- On-axis dynamically ranged beacon
- Fast optical shutter
- Direct wavefront measurement
- System optimization to support diverse beacon ranges



- **SHWFS spots representing zonal wavefront gradients**
- **Each SHWFS sub-aperture is smaller than the expected r_0**
- **Variance of the spot tilts is used to calculate r_0**
- ***Based on r_0* differencing within a “frozen” atm. window segmented C_n^2 can be calculated**

$$r_0 = \frac{0.299D}{(\sigma^2)^{3/5}}$$

$$C_{n_{seg}}^2 = \frac{\Delta r_0^{-5/3}}{.423k^2\Delta z}$$

Sensing Methodology: Algorithm to Produce C_n^2

- SHWFS spots representing zonal wavefront gradients
- Each SHWFS sub-aperture is smaller than the expected r_0
- Variance of the spot tilts is used to calculate r_0

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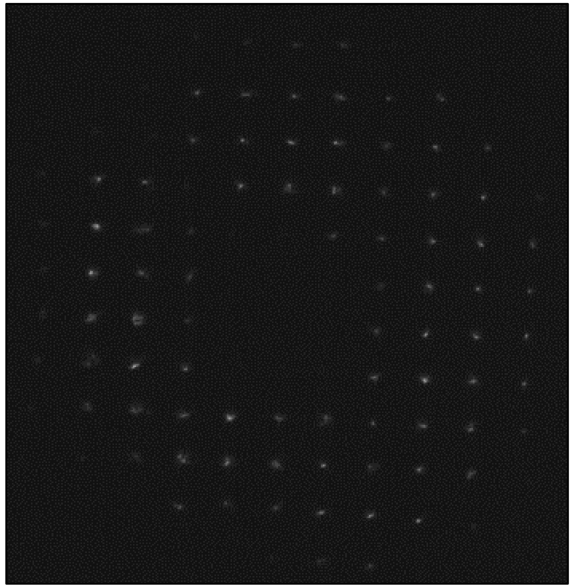
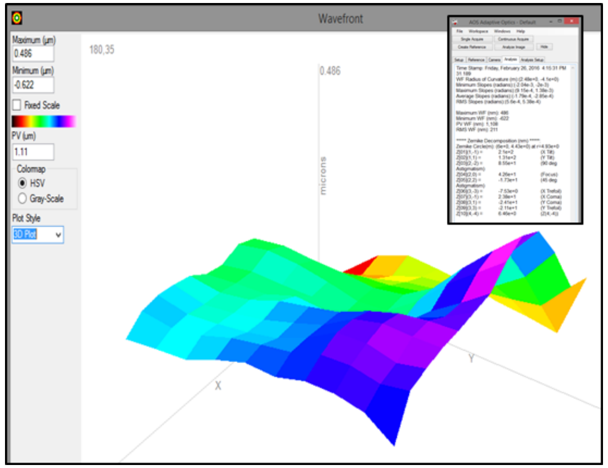
SHWFS Spots



Representative of a Wavefront



Wavefront

Maximum (µm): 0.486

Minimum (µm): -0.622

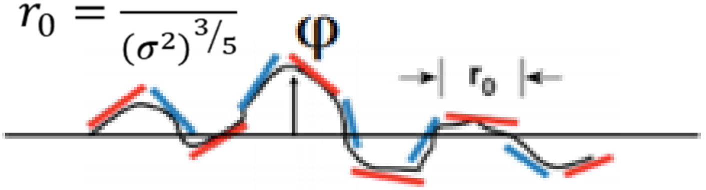
☐ Fixed Scale

PV (µm): 1.11

Colormap: ● HSV ○ Gray-Scale

Plot Style: 3D Plot

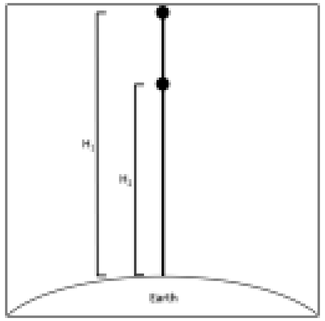
$$r_0 = \frac{0.299D}{(\sigma^2)^{3/5}}$$



r_0 = char. size of turbulent cells

φ = amplitude of wavefront excursions

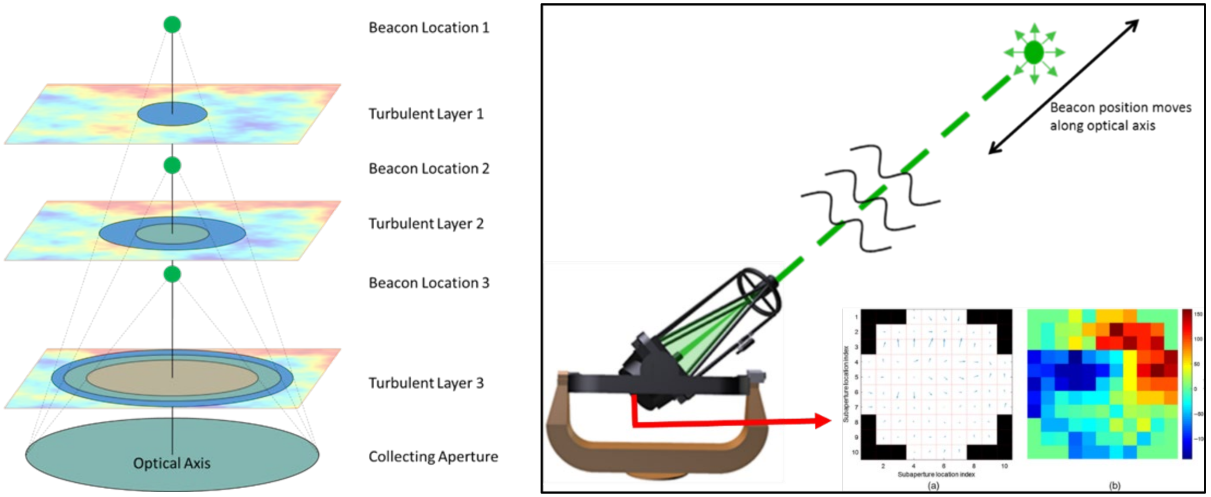
$$C_{n_{seg}}^2 = \frac{\Delta r_0^{-5/3}}{.423k^2\Delta z}$$



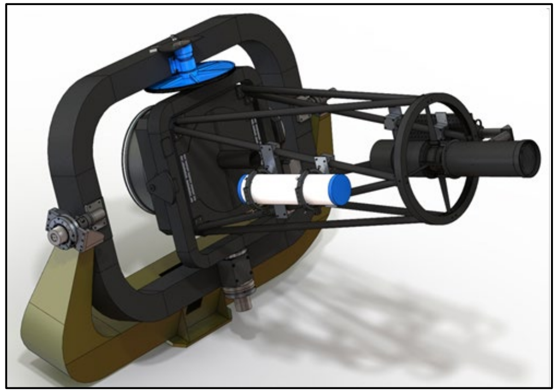
System Prototype: TARDIS

- Key features
  - Rayleigh beacon based design
  - Dynamic controlled shutter
  - Optimized design to support multiple beacon ranges
- Components
  - Telescope: F#:17.1, D = 0.6096 m
  - Laser: DP-527-8 (Photonics Inc.)
    - Pulse energy = 7.98 mJ
    - Pulse width = 7.2 ns
    - Repetition rate = 200 Hz
    - Beam quality = 1.72
  - Beam launch system
    - Max radius = 7.62 cm
  - Sensor: SHWFS
    - Light relay and control
    - Fast shutter: Pockels cell
    - SHWFS camera: Mako-G40B
    - 10 x 10 lenslet array

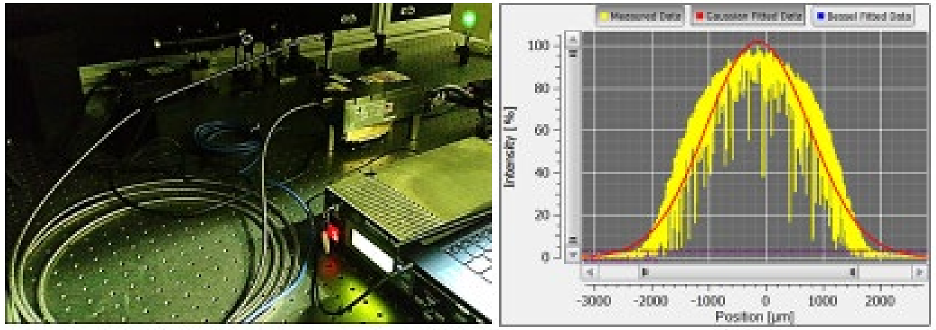
Overall Concept



Telescope



Laser System



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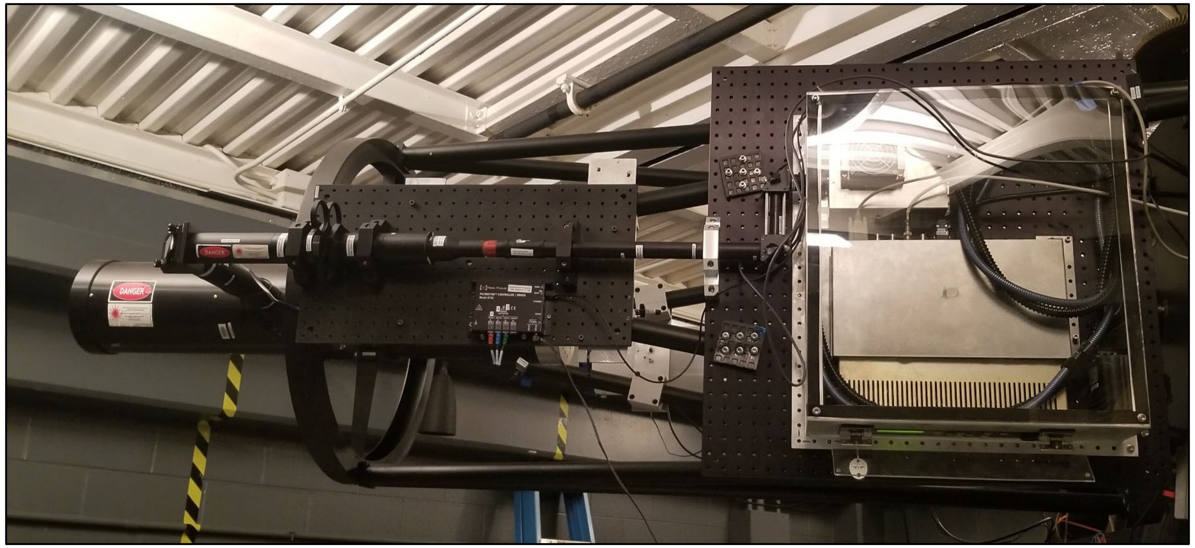
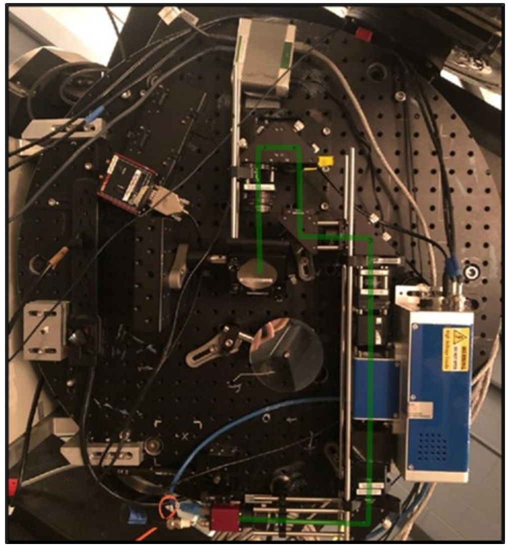
    - 10 x 10 lenslet array

Key Components
- ¼ wave plate
- Trombone
- Relay lenses
- Polarizers
- Iris
- Pockels cell
- SHWFS

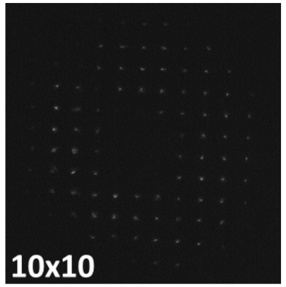
Beam Launch System



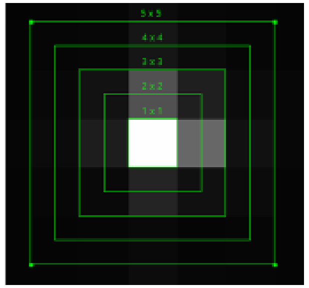
Sensing System



SHWFS Image



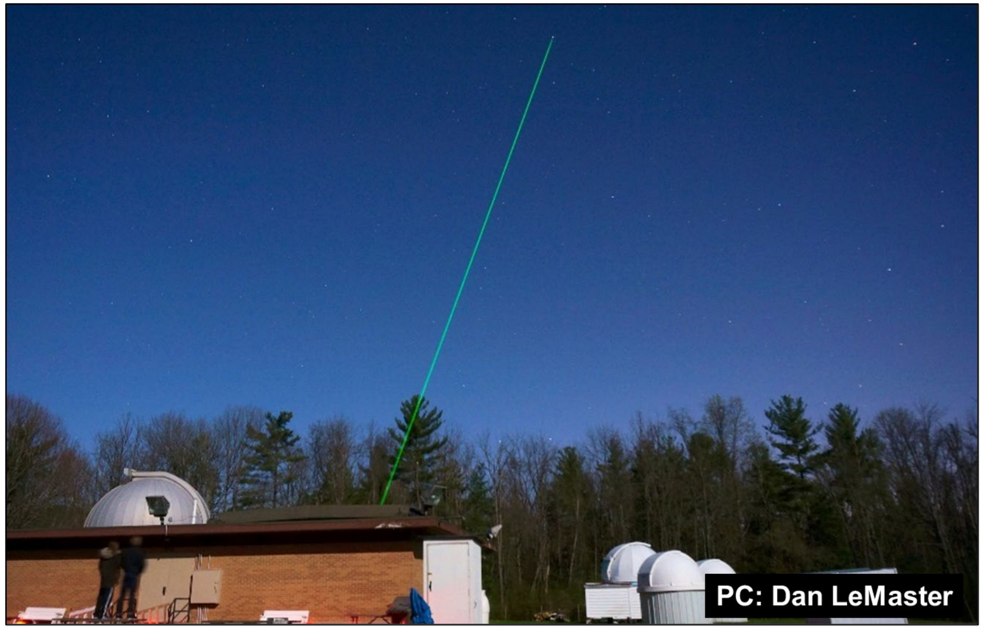
Single Spot



System Prototype: TARDIS

- Fully functioning and data collection ready
- Range: 0.45km to ~8km
- Depth: 100m to 450m
- Key camera settings:
    - Gain: 40dB
    - Gamma: 1.0
- Manning
    - 1 TARDIS operator
    - 2 aircraft spotters (FAA requirement)
- Data processing
    - Quasi-automated MATLAB scripts
    - File drop filtering, centroid thresholding configurations, range settings
- Fully automated laser firing windows coordinated with Laser Clearing House

PC: Steve Zuraski

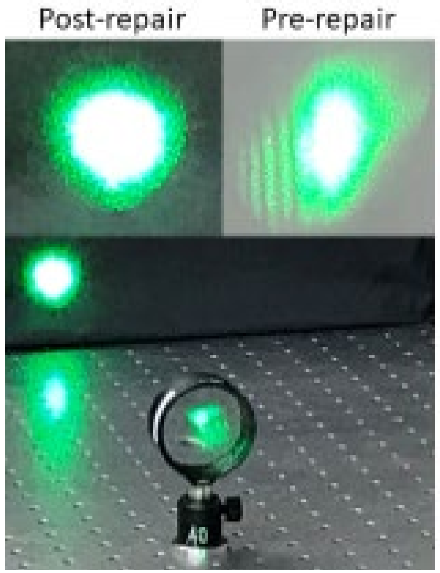


PC: Dan LeMaster

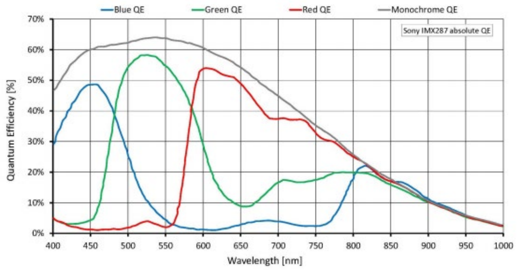
System Prototype: Lessons Learned

- First light success and challenges
  - Beam launch system worked
  - Light made it to camera
  - SHWFS spots were not present
- Trouble shooting improvements
  - SNR related
    - New lenslet design
    - Removal of optical fibers
    - More sensitive camera
    - Alignment of polarization state
  - Light blocking related
    - System timing control
    - Spatial light filtering
    - System focus measurement
    - Precision in light relay
  - Laser repair

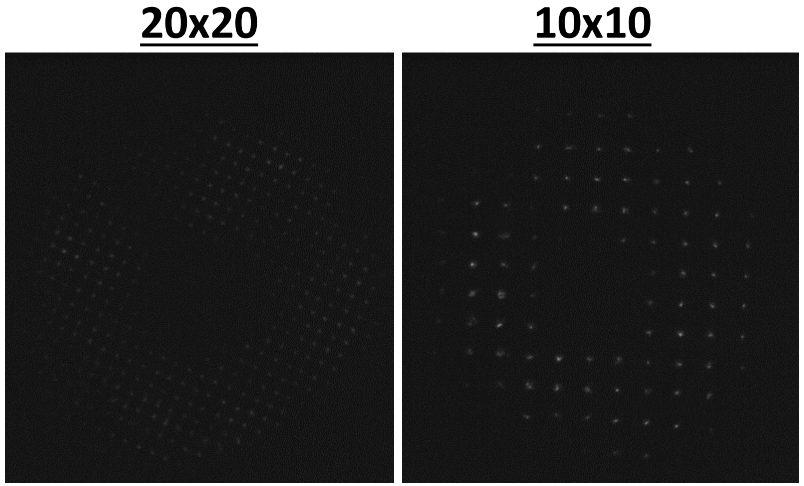
Laser Repair

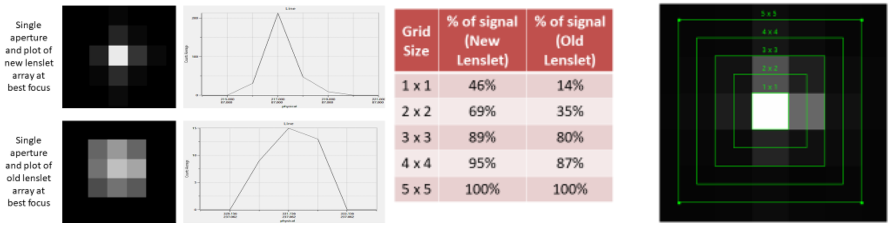


New Camera



New Lenslet Design





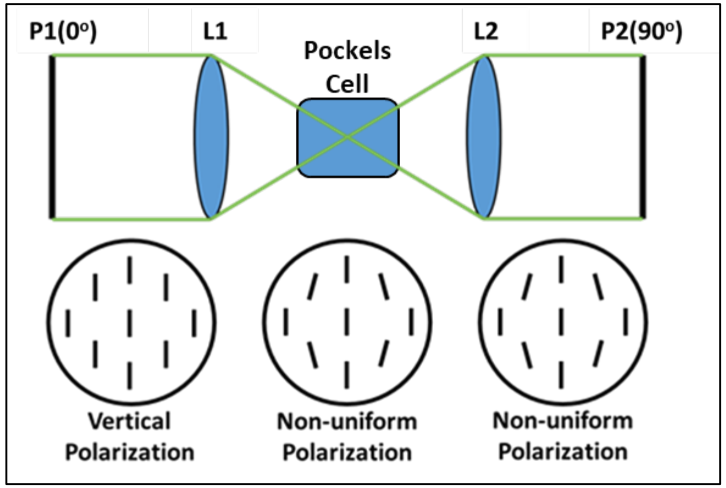
Grid Size	% of signal (New Lenslet)	% of signal (Old Lenslet)
1 x 1	46%	14%
2 x 2	69%	35%
3 x 3	89%	80%
4 x 4	95%	87%
5 x 5	100%	100%

Fig. 40. New lenslet array focal spot improvement showing higher concentration of energy in central pixel

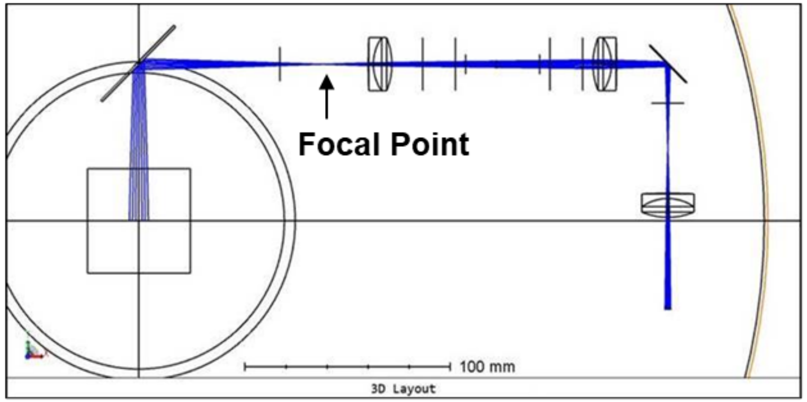
System Prototype: Lessons Learned

Polarization Pupil Analysis

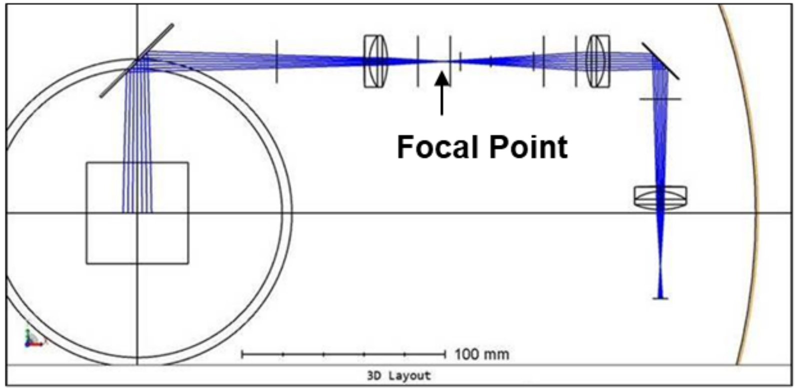
- Challenge: polarized pupil degradation due to focal shifts from the dynamically ranged beacon
    - Curvature present in the relayed pupil within the Pockels cell
    - Created light leakage in the fast optical shutter
    - Re-imaging optics redesign was required



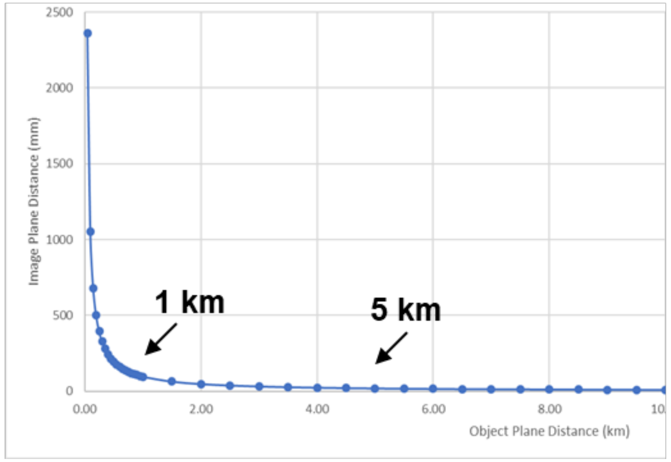
Light Relay for 5km source



Light Relay for 1km source



Focus shift vs. beacon range



System Prototype: Lessons Learned

Polarization Pupil Analysis

- Mathematical interpretation shows a departure from linear polarization state for converging or diverging light sources
- Jones Matrix: $J = te^{i\Phi}J_{\text{pol}}(d,\psi_p)J_{\text{ret}}(\phi,\psi_r)$

$$J_{\text{pol}}(d,\psi_p)\begin{pmatrix}1\\0\end{pmatrix} = \begin{pmatrix}1 + dcos2\psi_p\\ dsin2\psi_p\end{pmatrix}$$

$$J_{\text{ret}}(\phi,\psi_p)\begin{pmatrix}1\\0\end{pmatrix} = \begin{pmatrix}cos\phi - isin\phi cos2\psi_r\\ -isin\phi sin2\psi_r\end{pmatrix}$$

- Zemax analysis required to see effect in the polarization pupil

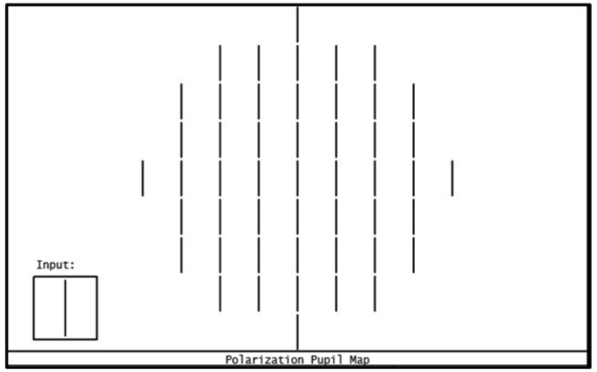
Experimental Analysis of the TARDIS Beam Relay:

- Emulated ranges by injecting focused light into the sensing system (1km, 1.2km, 1.5km, ∞)
- Recorded power meter readings to measure the Pockels cell light blocking ability
- There was significant light leakage as compared to an infinite source

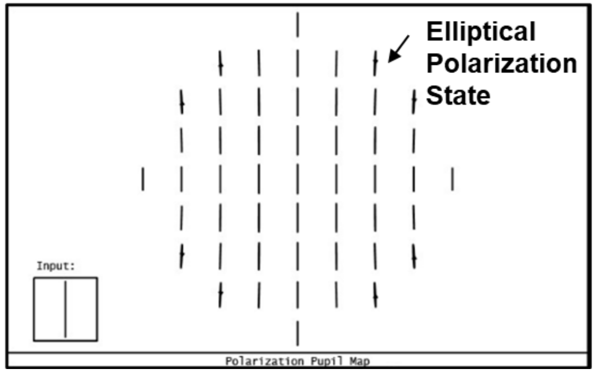
Solution:

- Beam relay reconfigure with longer relay lenses to minimize convergent rays within the Pockels cell
- Adjustable trombone light path that can be set in CONOPS planning

Collimated Beam

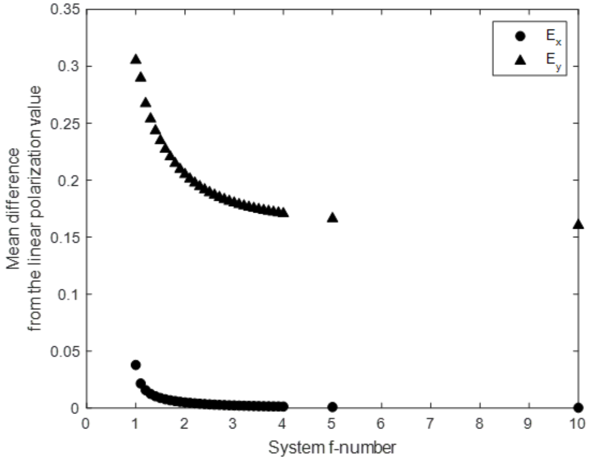


Convergent Beam

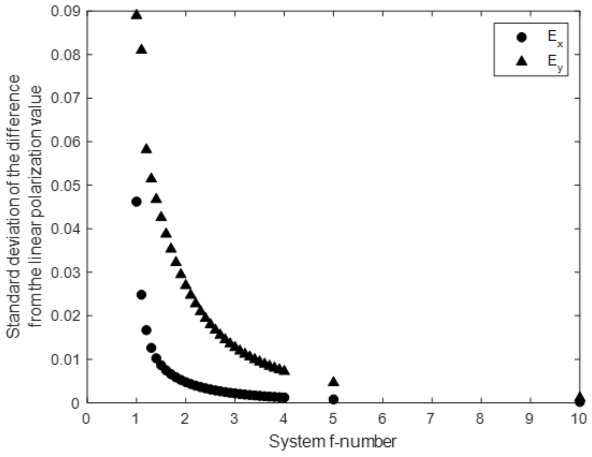


Elliptical Polarization State

Mean Difference vs. F#



Std Difference vs F#



Presentation Outline

- Research Motivation
- Background on Alternative Technologies
- Key Concepts from Theory
- Sensing Methodology
- System Prototype (TARDIS)
- Data Collections
  - Laboratory
  - On-Sky
- Next Steps
- Conclusion

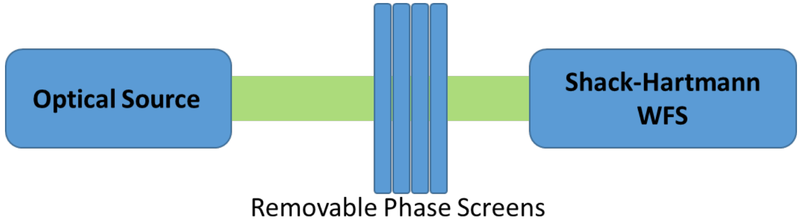
PC: Steven Zuraski

PC: Dan LeMaster

Data Collections: Laboratory

- Tabletop simplified experiment used to test TARDIS concept and data processing methods
- Used as a stepping stone for data processing automation and code development

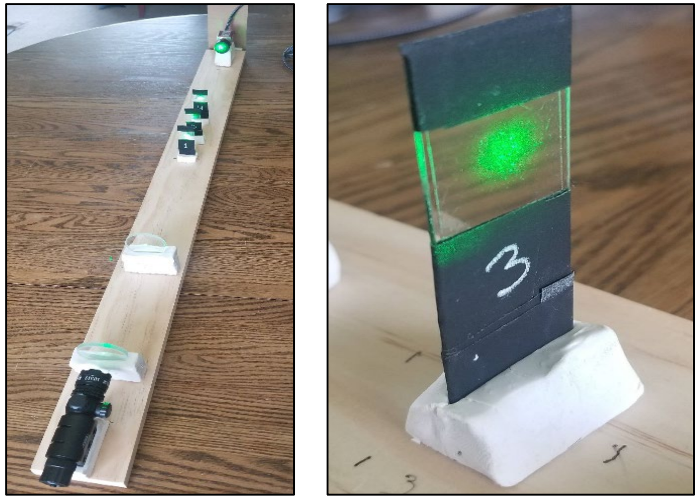
Setup



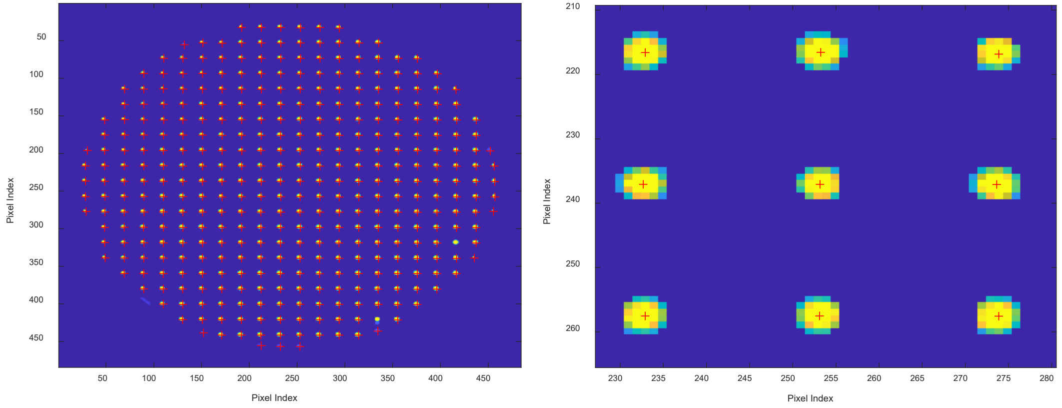
Optical Source

Shack-Hartmann WFS

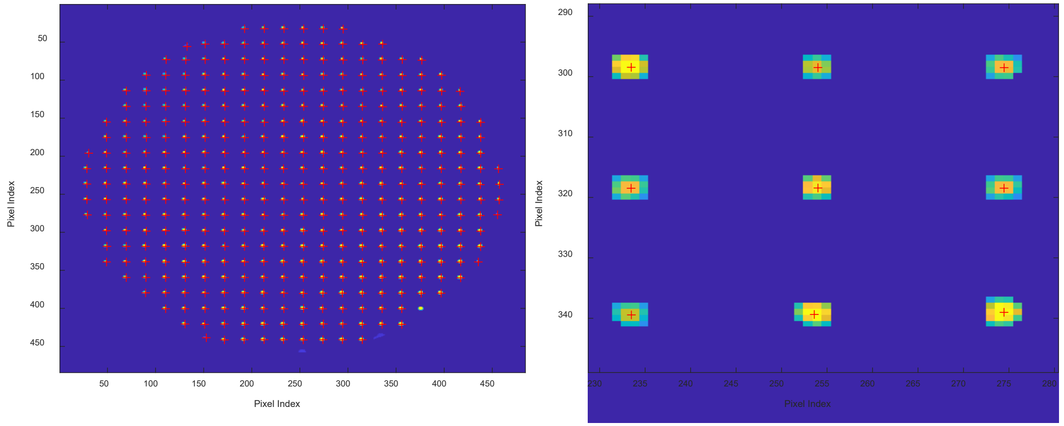
Removable Phase Screens



Reference Data



Wavefront Data

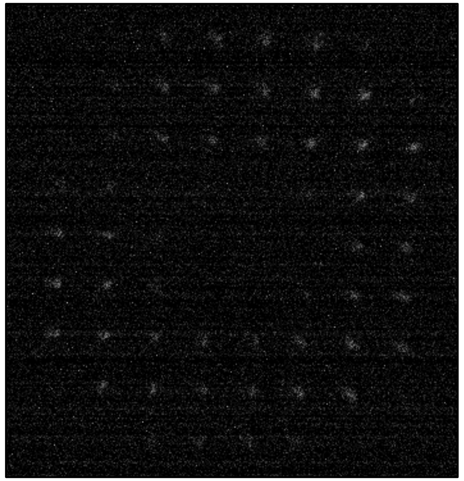


Results

	Screen 1	Screen 2	Screen 3
Calculated	0.0134	0.0119	0.0084
Truth	0.0134	0.0148	0.0105
Difference	0	0.0028	0.0021
% Error	0	18.90%	20.00%

Data Collections: How On-Sky Data is Processed

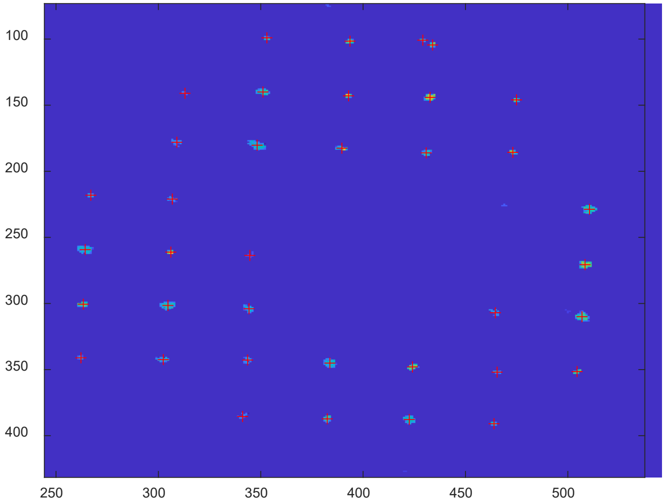
Raw Data



1. Filter noise
2. Threshold data
3. Centroid spots

- Iterate on all data
- Tag beacon range and sequence number

Processed Data



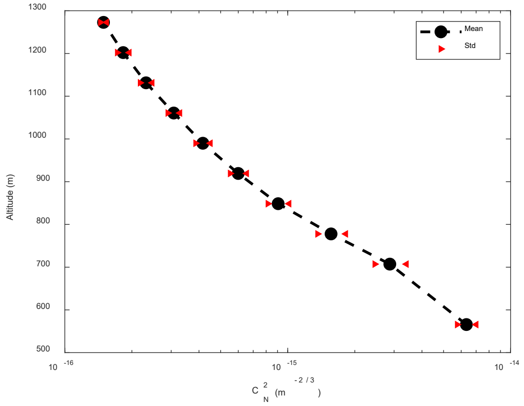
Calculations on All Data

1. Define common group of ROIs
2. Discard data groups that don’t fit ROI common group
3. Define spot center reference

Reprocess Data

1. Calculate tilts for all ROIs
2. Calculate r_0 assigned to each SHWFS spot image file
3. Assign beacon range value to each r_0
4. Group r_0’s into dynamic range sequences
5. Calculate C_n^2 profiles vs. range

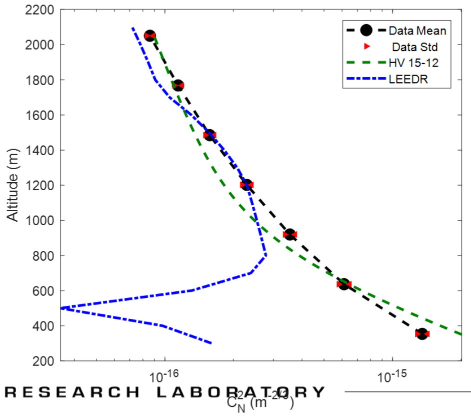
Plot Data



Compare to Turbulence Models

LEEDR Laser Environmental Effects Definition And Reference

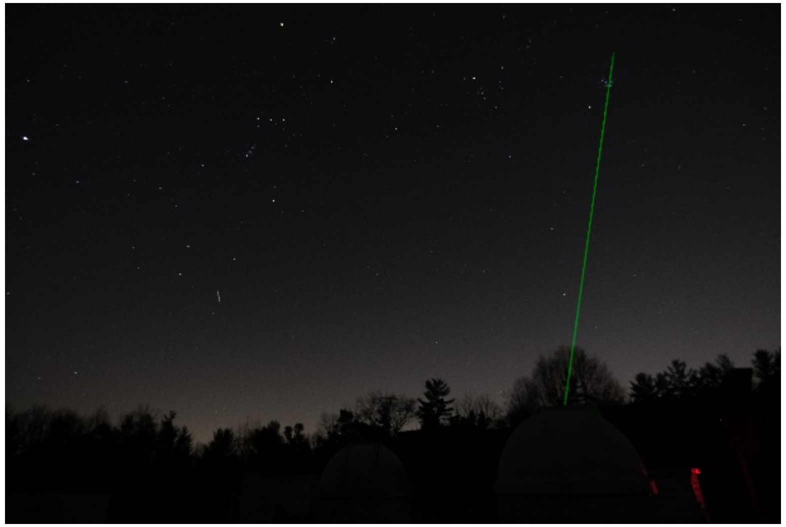
DELTA



Data Collections: On-Sky Setup Summary

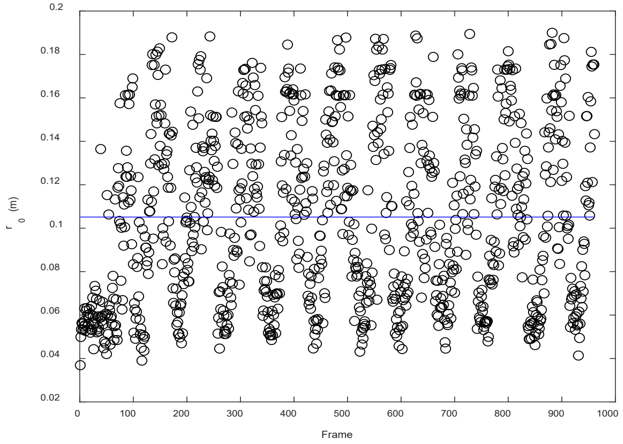
- Data Collect 1
  - May 12th, 2021
  - 23:32 - 23:36 UTC
  - 20,556 frames
  - $\Delta z = 450$m
- Data Collect 2
  - May 13th, 2021
  - 00:57 - 01:03 UTC
  - 37,691 frames
  - $\Delta z = 450$m
- Data Collect 3
  - June 6th, 2021
  - 03:43 - 03:52 UTC
  - 59,132 frames
  - $\Delta z = 450$m
  - Gamma: changed 0.4 to 1.0

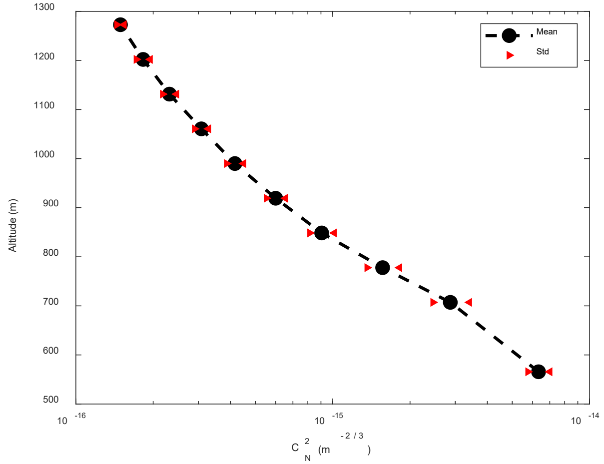
	Ranges (m)	Slant Angle (degrees)	Data Quality (poor, average, good)
Data Collect 1	800, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800	45	Average
Data Collect 2	300*, 600, 900, 1200, 1500, 1800, 2100, 2400, 2700, 3000, 3300 *Poor data quality due to defocused SHWFS spots	45	Poor*, Average
Data Collect 3	500, 900, 1300, 1700, 2100, 2500, 2900, 3300	45	Good

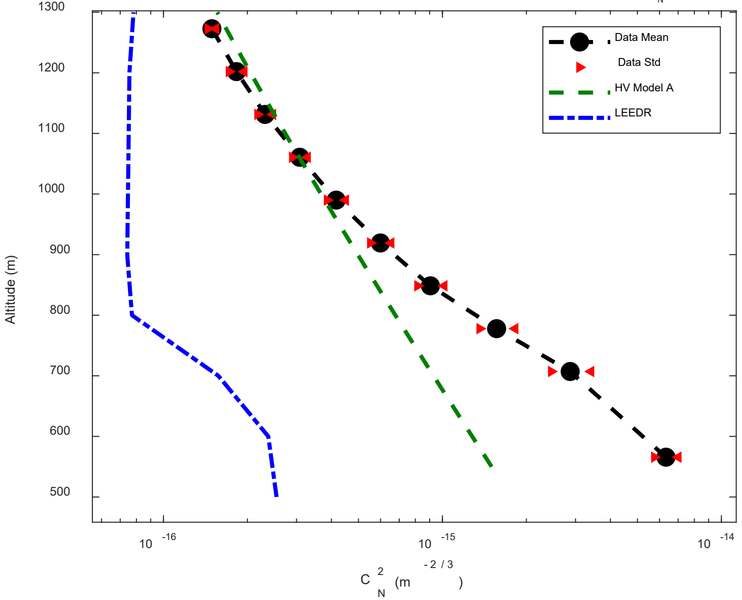


Data Collections: On-Sky Results

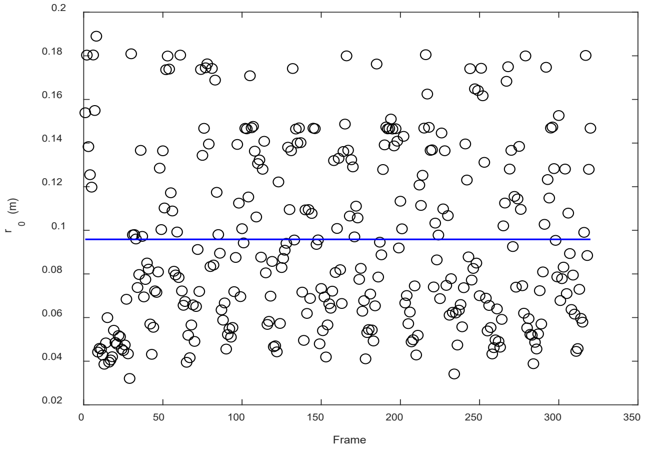
Data Collect 1

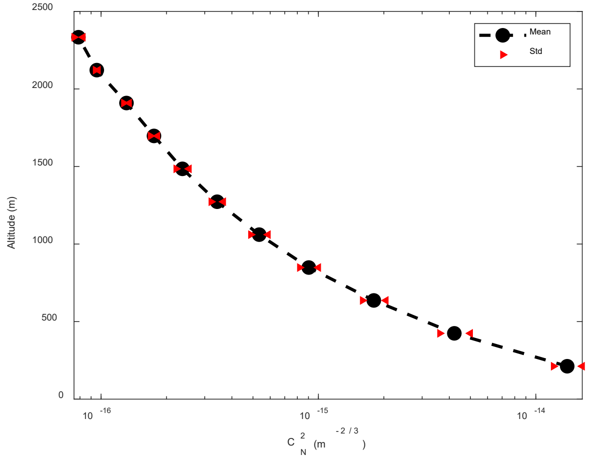


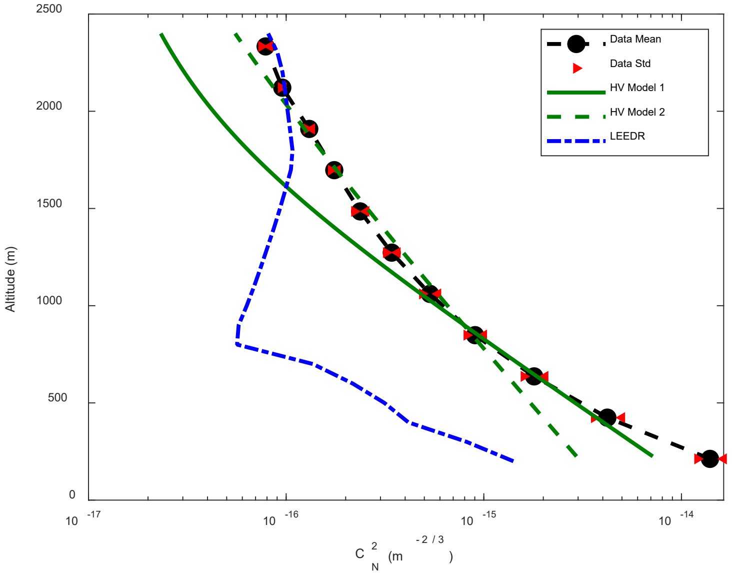




Data Collect 2





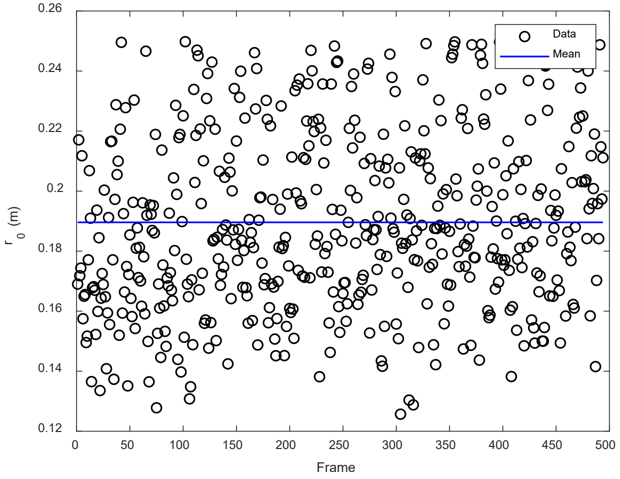


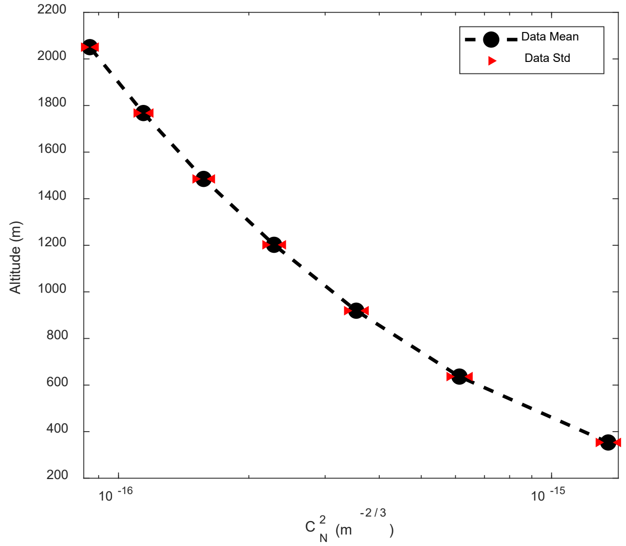
Data Collections: On-Sky Results Continued

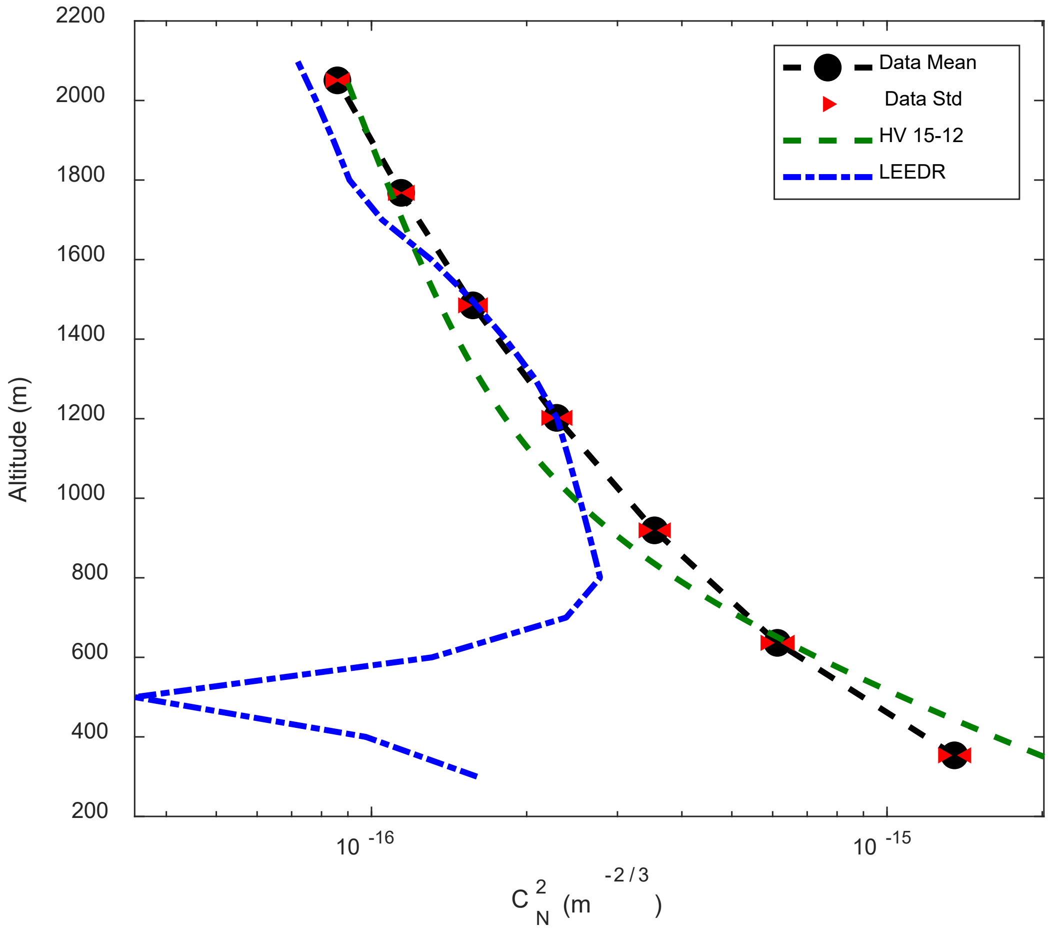
Discussion

- This is the best data set
- Gamma setting changed
  - Reduced background noise
  - Lowered signal magnitude
  - Centroiding threshold reduced from 35% to 15%
- Observation comments:
  - Night was calmer and clearer
- Weather model matches well at altitudes >800m
- Low altitude strength decrease missed due to Δz setting of 450m

Data Collect 3







Data Collections: On-Sky Example Profile

r_0 vs. Altitude

C_n^2 vs. Altitude

Each Profile is Captured in ~1/30th of a second

Data Collections: On-Sky Laser Beam Images


PC: Steve Zuraski


PC: Matthew Wilson

Next Steps

- Improvements to TARDIS
  - Dynamically ranged beacon with dynamic range depth settings
  - Develop a near-real time data processor
- Additional research topics
  - Improvements to centroiding accuracy
  - Centroiding in the presence of defocus
  - SLODAR inspired enhanced range resolution (AFOSR proposal)
- More data collections
  - Joint data collections with DELTA-Sky
  - Reduced Δz to 100m to map out low altitude bump in profile
  - Seek collaborations utilizing alternate C_n^2 measurement systems for cross-comparison

Conclusions

- TARDIS provides a new and innovative method for quantifying the strength of atmospheric turbulence
- Novel contributions to the research community
  - First dynamically ranged beacon within “frozen” atmosphere time window
  - Utilization of direct measurement of full wavefront to produce C_n^2 measurement, strong correlation statistics
  - Engineering design with no moving parts, mitigates dynamic refocusing
  - Analysis of Pockels cell light leakages from dynamic beacon ranges
  - Signal processing algorithms to get from r_0 to C_n^2
- High quality data seems to match well with weather parameter derived models
- Opportunity for continued research using TARDIS
  - Comparisons to other methodologies (DELTA-Sky, NWP models, etc.)

Questions?

Backups

Publication List

- Journal Articles:
  - S. Zuraski, E. Beecher, J. McCrae, and S. Fiorino, "Turbulence profiling using pupil plane wavefront data derived Fried parameter values for a dynamically ranged Rayleigh beacon," Opt. Eng. 59(8), 081807 (2020), doi: 10.1117/1.OE.59.8.081807.
  - S. Zuraski, S., E. VanTilburg, M. Wilson, J. E. McCrae, & S. T. Fiorino, (2021). Implications of polarized pupil degradation due to focal shifts in dynamically ranged Rayleigh beacons. *Applied Optics*, *60*(3), 606-615.
- Conference Papers
  - S. Zuraski, S. Fiorino, J. McCrae, E. VanTilburg, L. Weisenbach, M. Wilson, “Vertical profiles of turbulence measured with a Rayleigh beacon.” *SPIE Optical Engineering and Applications Symposium, 2021*
  - S. Zuraski, “Turbulence profile measurement with a dynamically ranged Rayleigh beacon.” *Propagation Through and Characterization of Atmospheric and Oceanic Turbulence,* OSA Imaging and Applied Optics Congress*,* 2021
  - S. Zuraski, J. McCrae, S. Fiorino. "Focal anisoplanatism influence on dynamically ranged Rayleigh beacon measurements." *Unconventional Imaging and Adaptive Optics 2020*. Vol. 11508. International Society for Optics and Photonics, 2020
  - S. Zuraski, E. Beecher, C. Carr, T. Payne, A. Battle, L. Guliano, S. Fiorino, “Turbulence and aerosol research dynamic interrogation system testing,” in *Adv. Maui Opt. and Space Surveillance Technol. Conf.* 2018
  - S. Zuraski, S. Fiorino, E. Beecher, N. Figlewski, J. Schmidt, J. McCrae. "Electro-optic testbed utilizing a dynamic range gated Rayleigh beacon for atmospheric turbulence profiling." Optics in Atmospheric Propagation and Adaptive Systems XIX. Vol. 10002. International Society for Optics and Photonics, 2016

Data Collect 3 with two LEEDR Options