The Effect of Atmospheric Turbulence in Astrophysical Applications

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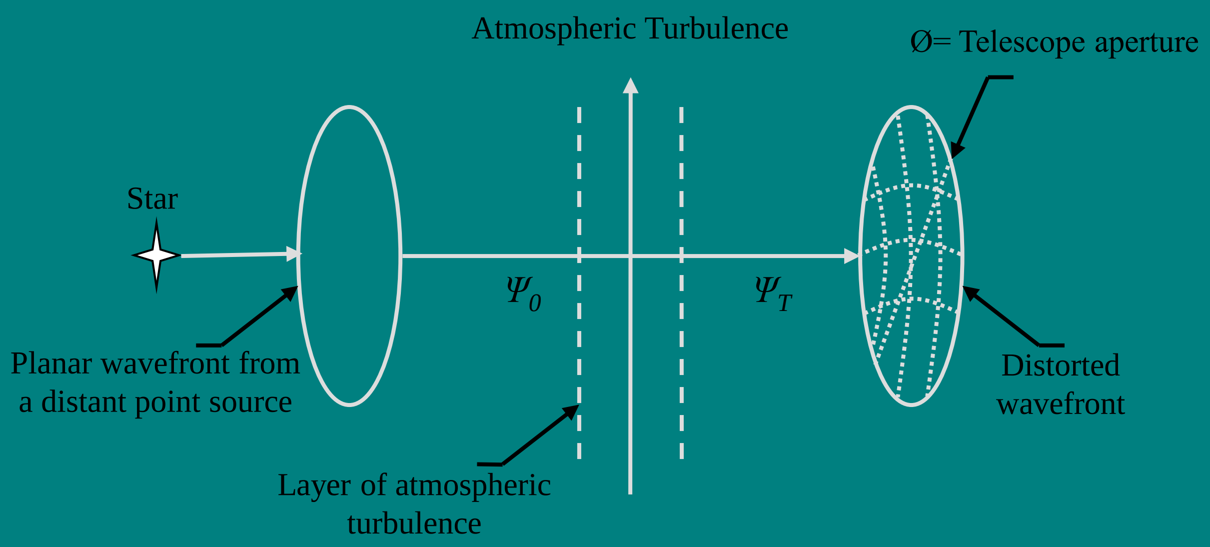
IŞIK ÜNİVERSİTESİ

Wavefront Phase Distortions



$\Psi_0 = A\, e^{i\varphi}$ and $\Psi_T = A\, e^{i\varphi(r,\rho,\, t)}$

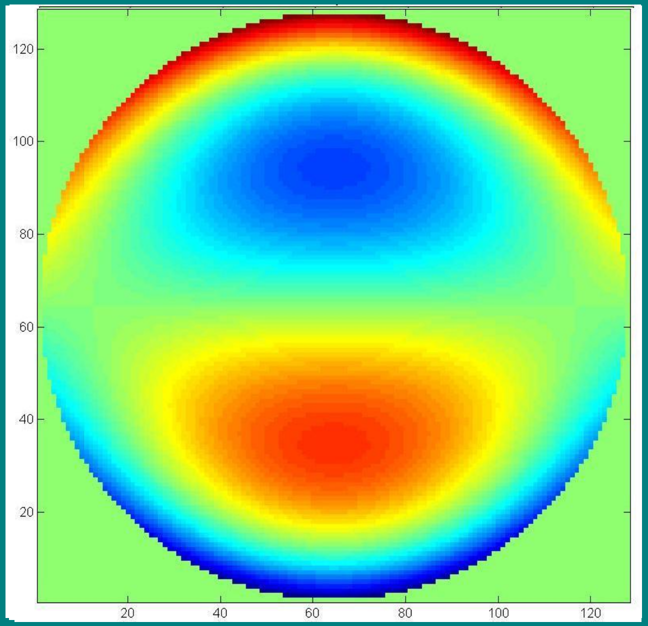
- ***A*** **is the wave amplitude, and** φ **is the phase of the field fluctuation.**
- **A surface over which** φ **takes the same value is called the wavefront surface.**

Wavefront Phase Distortions

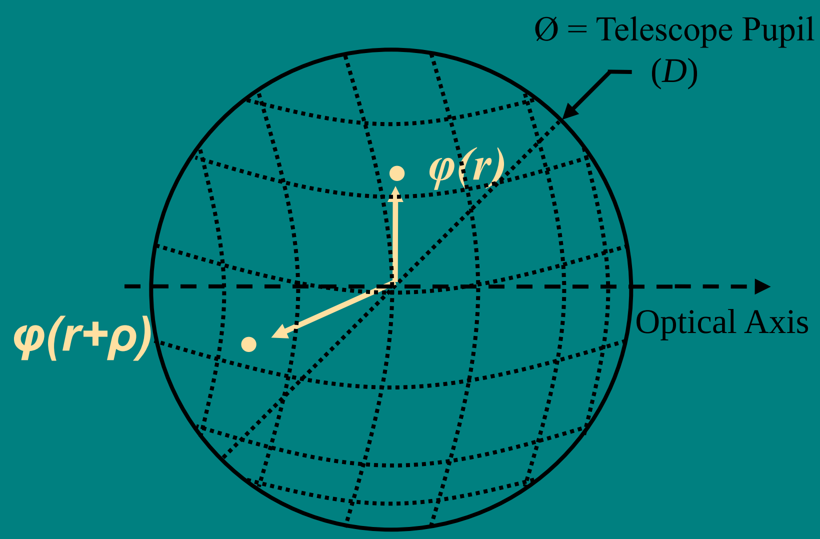
• In an optical system, it is sometimes useful to present the phase (φ) as a 2D surface over a circular pupil (e.g., telescope pupil).

• The derivation from the flat (planar) wavefront is the wavefront error and is conveniently represented by a series of orthogonal polynomials over the circular pupil (e.g., Zernike Polynomials).

“Astig“D“Coma”



Wavefront Phase Measurement



Top view of the wavefront phase when tip/tilt modes are removed

- The deformation on the wavefront surface after turbulence can be given as

$$\delta = \int n(z)dz$$

n(z) is the refractive index fluctuation

- The phase fluctuations is related to wavefront surface deformation by

$$\varphi = k\int n(z)dz$$

k is the wave number (2π/λ), and λ is the wavelength of the incoming beam

- The structure function of the phase aberrations within the telescope's aperture plane (*D*)

$$D_\varphi(\vec{\rho}) = \left\langle \left|\varphi(\vec{r}+\vec{\rho}) - \varphi(\vec{r})\right|^2 \right\rangle_D$$

$\langle \ldots \rangle_D$ represents the radial average over the pupil

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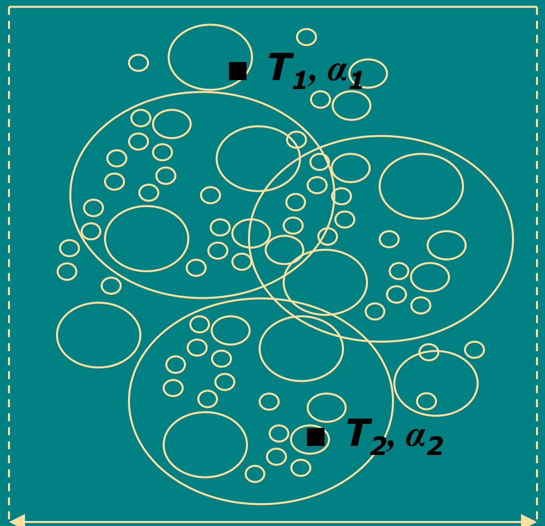
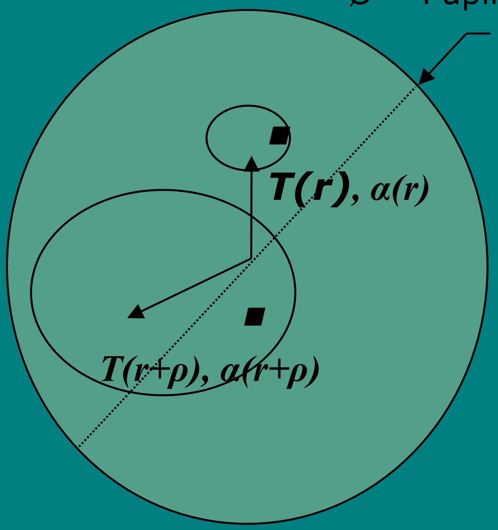
Kolmogorov's Theory of Optical Turbulence





$$D_T(\vec{\rho}) = \left\langle \left| T(\vec{r}+\vec{\rho}) - T(\vec{r}) \right|^2 \right\rangle_D \Rightarrow D_T(\vec{\rho}) = C_T^2 \rho^{2/3} \Rightarrow C_N^2 = \left(\frac{\alpha_n P}{T^2} \right)^2 C_T^2$$

DT(ρ): Structure Function of the temperature field; r&ρ: Temperature value of the phase aberration at a point r and the value at a nearby point r+ρ; T: Temperature; CT2: Structure constant of the temperature field; P: Air pressure; CN2: structure constant of the refractive index

Fried's Coherence Length (r_0)

A widely used descriptor of the level of atmospheric turbulence at a particular site

$$D_{\varphi}(\vec{\rho}) = 2.91 k^2 (\cos\gamma)^{-1} \int C_N^2(h)\, dh\, \rho^{5/3} = 6.88(\rho / r_0)^{5/3}$$

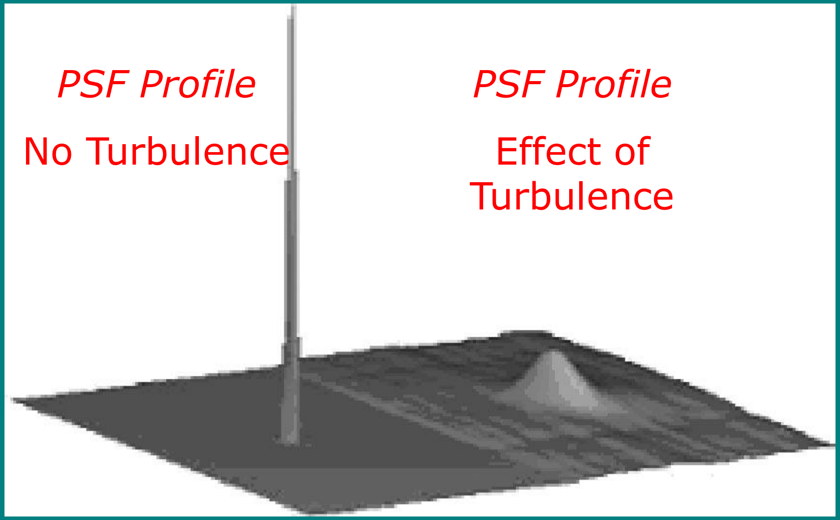
k: The wave number (2π/λ); γ: The angular distance of the point source from the zenith; The quantity (cos γ)-1: The air mass; r0: The Fried coherence length

$$r_0^{-5/3} = 0.4234(2\pi/\lambda)^2 \int_0^{\infty} C_N^2(h) dh$$

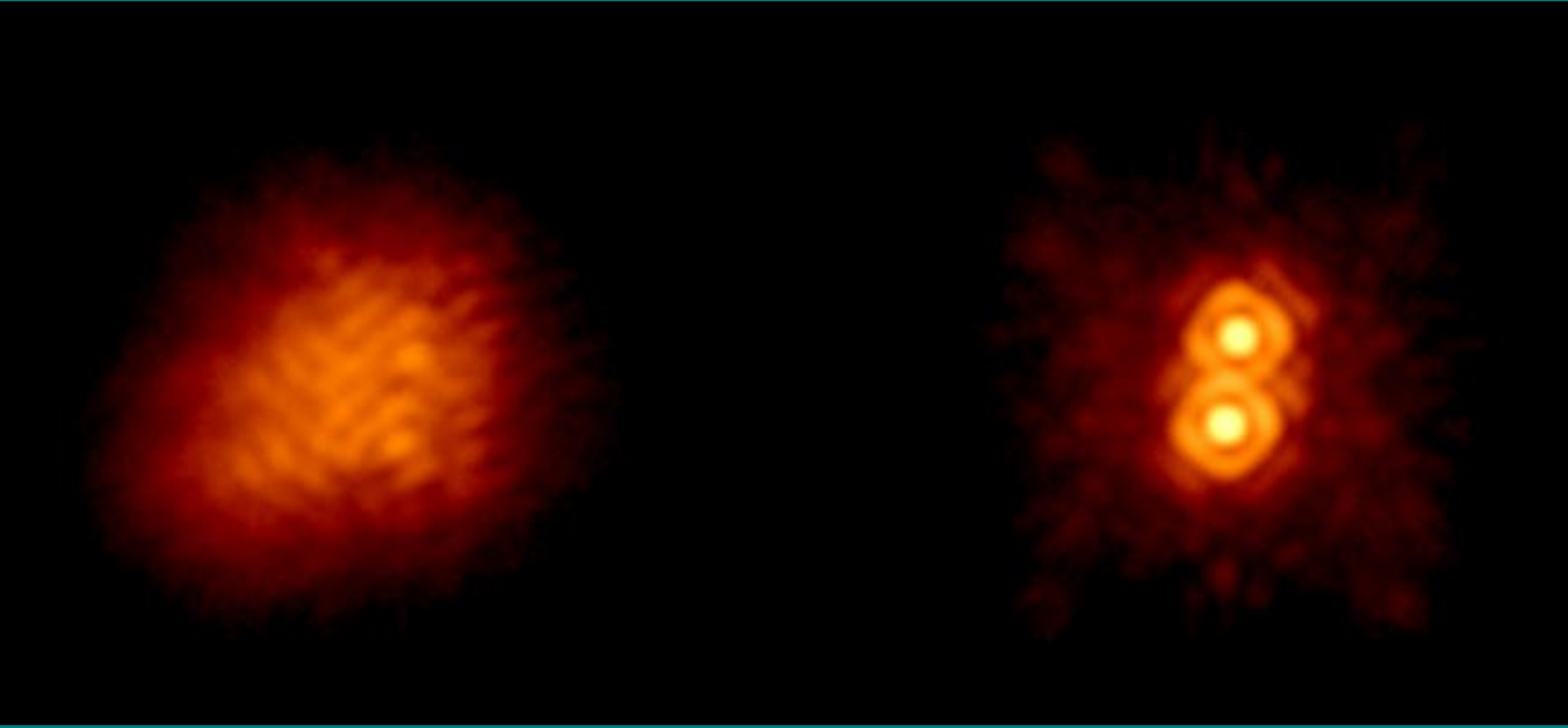
and

$$\sigma_1^2 = 1.03(D/r_0)^{5/3}$$

σ2: The mean square error of the wavefront phase aberrations over a circular area of diameter D. Hence, one interesting property of Fried's coherence length is that the root mean square (rms) of the phase distortion over a circular area of diameter r0 is about 1 radian

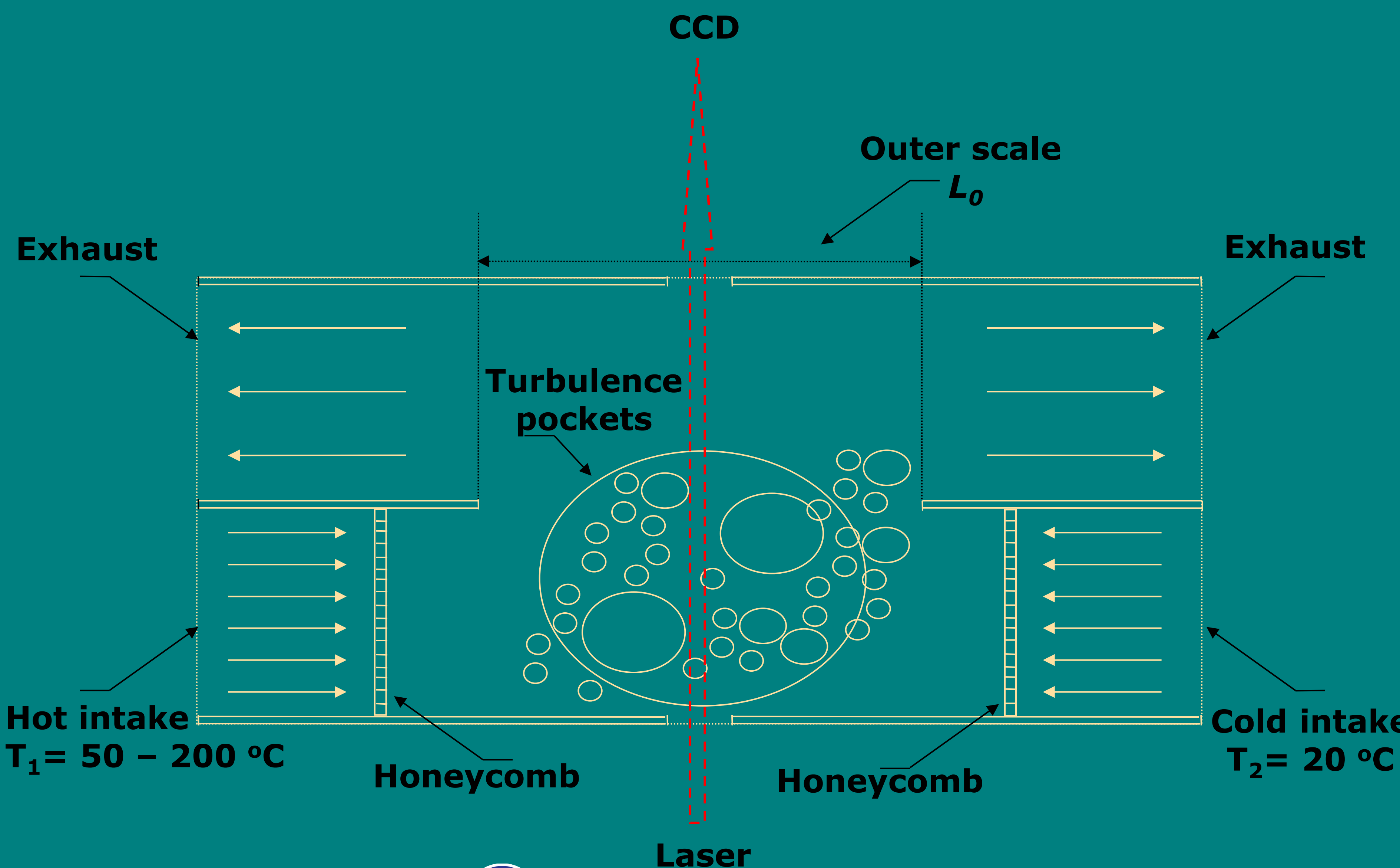


The Effect of Turbulence Can then be Simply Summarized as

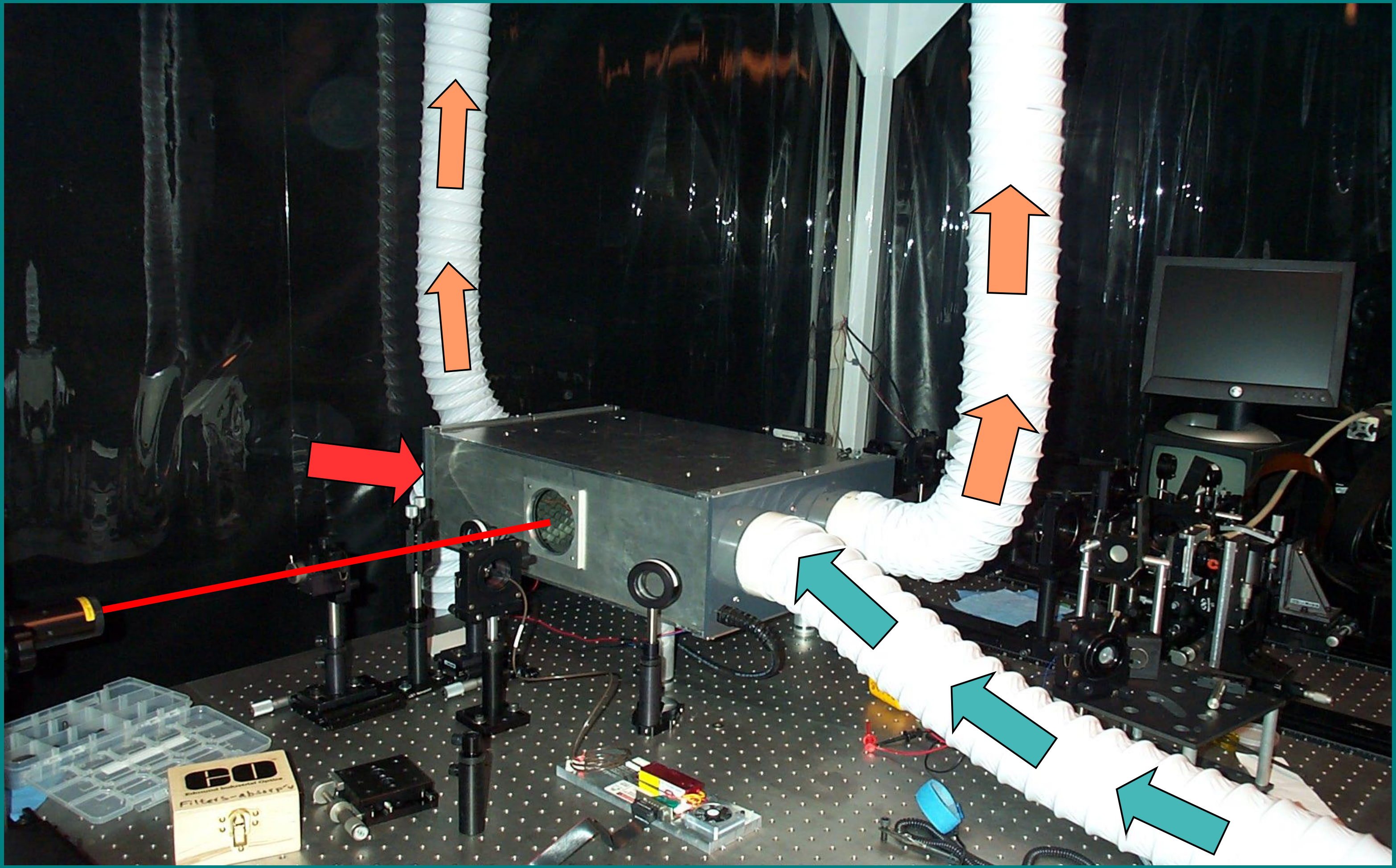


BAD!!

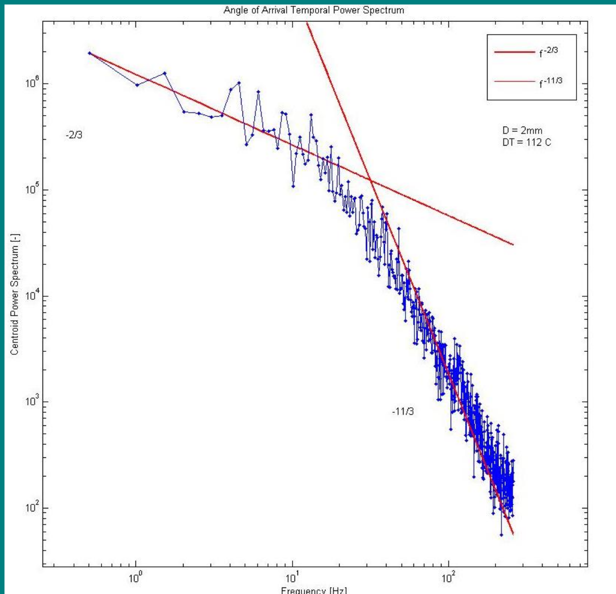
DAG Turbulence Generator Design

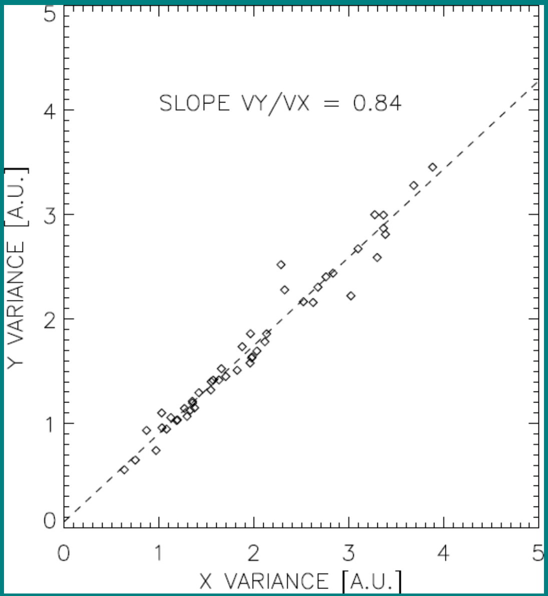


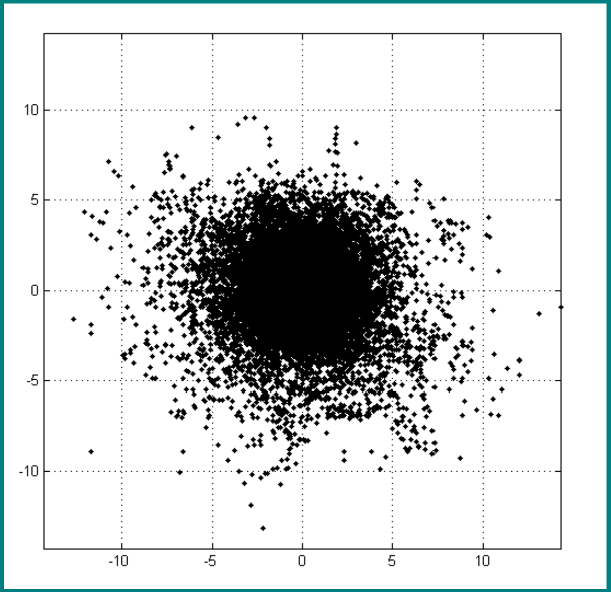
DAG Turbulence Generator



DAG TG Expected Results







- For mono-layer turbulence, the two lines on the graph (left) show the temporal power spectrum of the turbulence with respect to the Kolmogorov's model ($f^{-2/3}$ and $f^{-11/3}$ power laws). In the same graph, the depreciation in high and low temporal frequencies signifies the effect of the outer and the inner scales of the turbulent box. Also the qualitative behaviour of Kolmogorov's Law is proven. The knee frequency is found to be 30 Hz.

- Middle graph shows that the AoA variance is nearly isotropic $\sigma_x^2/\sigma_y^2=0.84$ for all beam diameters and temperature differences.

- The graph (right) also shows the isotropy of the turbulence as expected by Kolmogorov's atmospheric turbulence theory.

DAG TG Expected Results

ΔT [^{0}C]	$C_N^2\Delta h$ X [$e^{-10}m^{1/3}$]	r_0 X [mm]	$C_N^2\Delta h$ X [$e^{-10}m^{1/3}$]	r_0 Y [mm]	$C_N^2\Delta h$ [$e^{-10}m^{1/3}$]	r_0 [mm]
35	2.37	2.68	2.29	2.94	2.23	2.81
46	4.39	2.17	4.04	2.41	4.04	2.29
68	4.42	2.15	4.29	2.27	4.17	2.15
102	5.47	1.83	4.83	1.97	5.15	1.90
145	6.16	1.70	5.53	1.82	5.85	1.76

- Table on the right show "C_N^2" values obtained in the box, which can also be adjusted to a higher or lower strength by changing the diameter of the pupil, and the settings of the heaters. From these results it can be concluded that the "C_N^2" values inside the box are compatible with the theoretical values in the real atmosphere.

Conclusions

- The Kolmogorov's theory and the spatio-temporal properties of the generated turbulence will be in a very good agreement, including the effect of the outer and inner scales.
- From the AoA experiment previously performed, it can be concluded that the generated turbulence is isotropic.
- D/r_0 measurements are compatible with most astronomical sites.
- The turbulence strength is adjustable compared to more expensive solutions as static phase screens.
- The device can be used with confidence to emulate a realistic turbulence in a controllable manner.

So if we take the atmospheric turbulence as a disease, the the cure will be the "Adaptive Optics Systems" that'll be explained in the next talk.

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