Propagation and Adaptive Optics

6. The Atmosphere

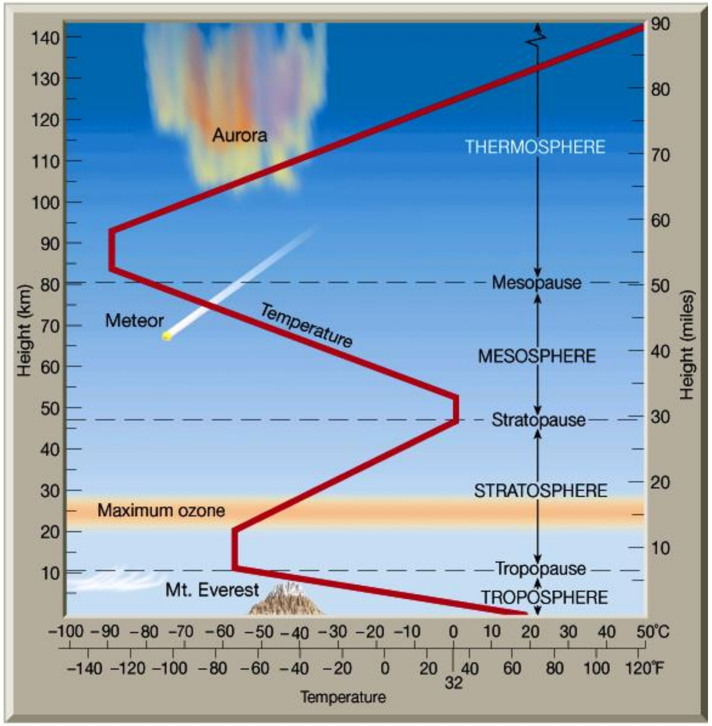
- 6.1 Atmospheric Structure
- 6.2 Atmospheric Effects
- 6.3 Adaptive Optics

A description of the atmosphere and its effect on a high energy laser beam are presented to understand the conditions needed for optimal performance of the laser weapon system. Adaptive optics mitigation strategies are also presented.

The Atmosphere

Atmospheric Structure

The atmosphere may be divided into several distinct layers.



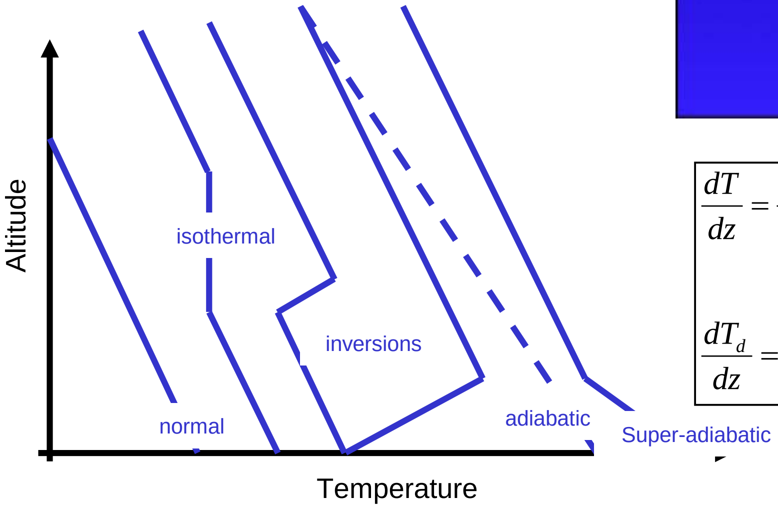
The stratosphere starts just above the troposphere and extends to 50 kilometers (31 miles) high. Compared to the troposphere, this part of the atmosphere is dry and less dense. The temperature in this region increases gradually to -3 degrees Celsius, due to the absorption of ultraviolet radiation. The ozone layer, which absorbs and scatters the solar ultraviolet radiation, is in this layer. Ninety-nine percent of "air" is located in the troposphere and stratosphere. The stratopause separates the stratosphere from the next layer.

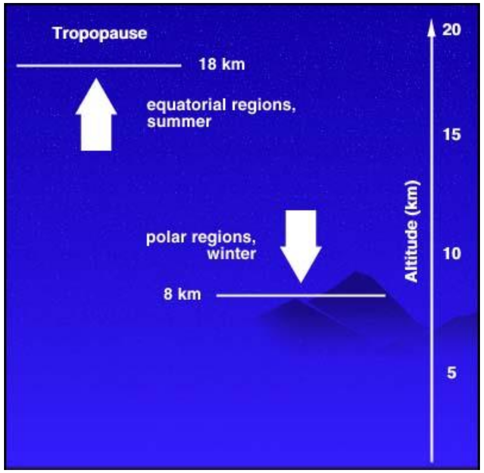
The troposphere starts at the Earth's surface and extends 8 to 14.5 kilometers high (5 to 9 miles). This part of the atmosphere is the most dense. As you climb higher in this layer, the temperature drops from about 15 to -52 degrees Celsius. Almost all weather is in this region. The tropopause separates the troposphere from the next layer. The tropopause and the troposphere are known as the *lower atmosphere*.

The Atmosphere

Atmospheric Structure

Moist Adiabatic Lapse Rates (°C/km)	-40 C	-20 C	0 C	20 C	40 C
P = 1000 mbar	9.5	8.6	6.4	4.3	3.0
P = 800 mbar	9.4	8.3	6.0	3.9	
P = 600 mbar	9.3	7.9	5.4		
P = 400 mbar	9.1	7.3			
P = 200 mbar	8.6				

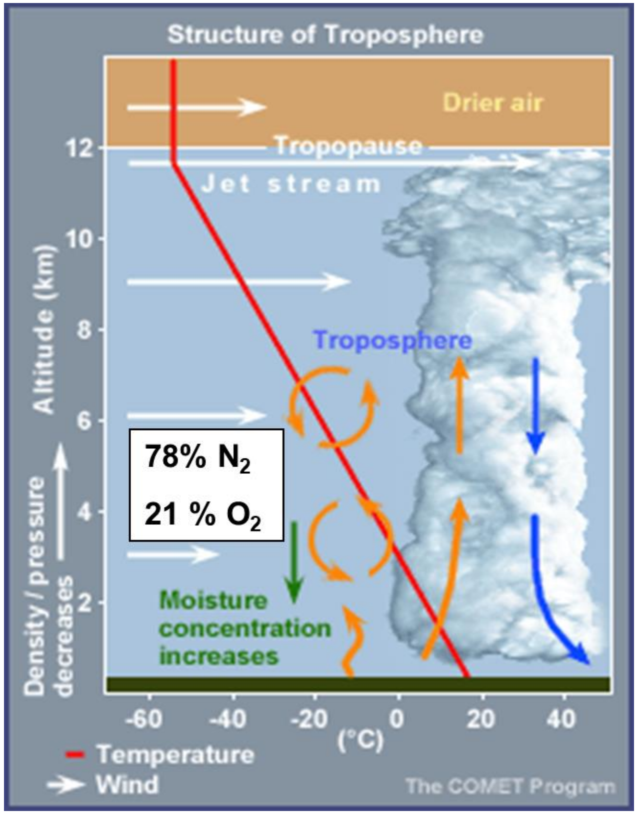




$$\frac{dT}{dz} = \frac{g}{c_p} = -\Gamma_{adiabatic} = -9.8\ \text{K km}^{-1}$$

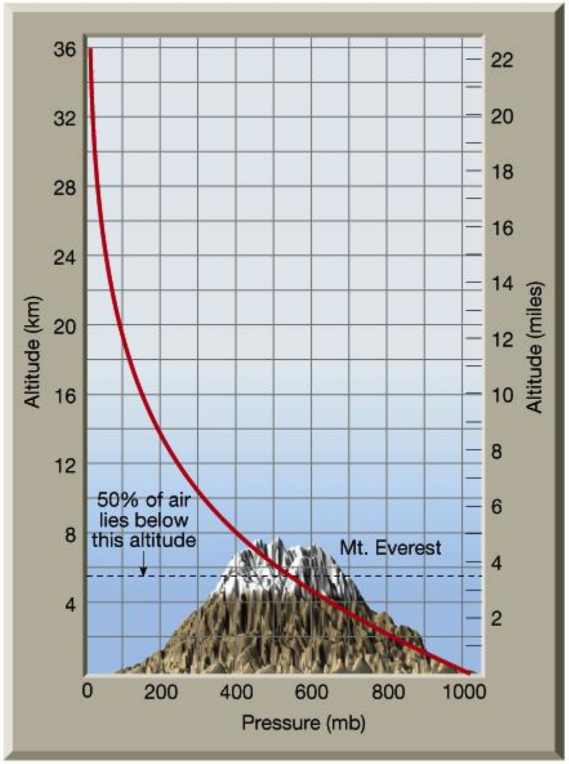
Dry, adiabatic lapse rate Γ=9.8 C/km

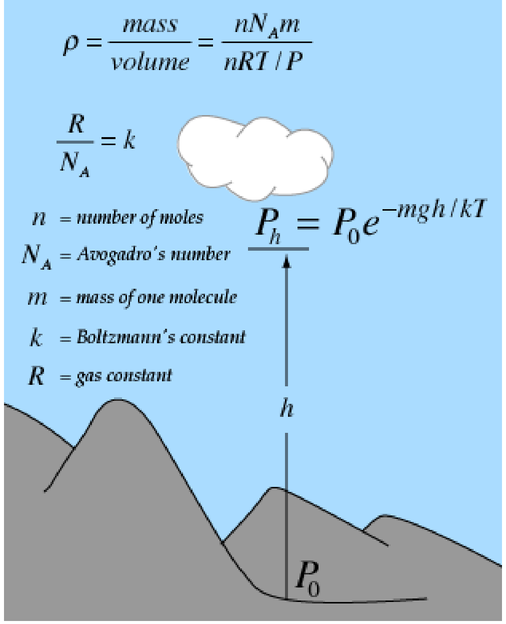
$$\frac{dT_d}{dz} = \frac{g}{\varepsilon l_v}\frac{T_d^2}{T} = -1.8\ \text{K km}^{-1}$$



The Atmosphere

Atmospheric Structure





$$\rho = \frac{mass}{volume} = \frac{nN_A m}{nRT/P}$$

$$\frac{R}{N_A} = k$$

n = number of moles
N_A = Avogadro's number
m = mass of one molecule
k = Boltzmann's constant
R = gas constant

$$P_h = P_0 e^{-mgh/kT}$$

Inches of Mercury → **("Hg)**
Atmospheres → **(atm)**
Kilopascals → **(kPa)**
Millibars → **(mb)**

29.92 "Hg = 1.0 atm = 101.325 kPa = 1013.25 mb

Pressure decreases exponentially, if temperature is incorrectly assumed constant.

P_o = 29.92 inches Hg

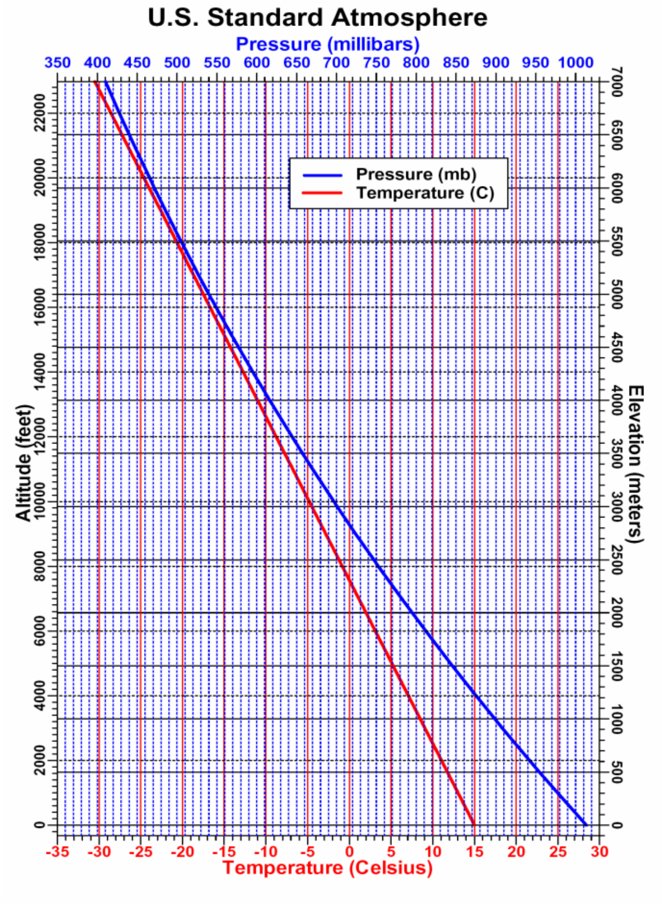
Scale height is:

$1/z_o$ = mg/kT = 7.4 km

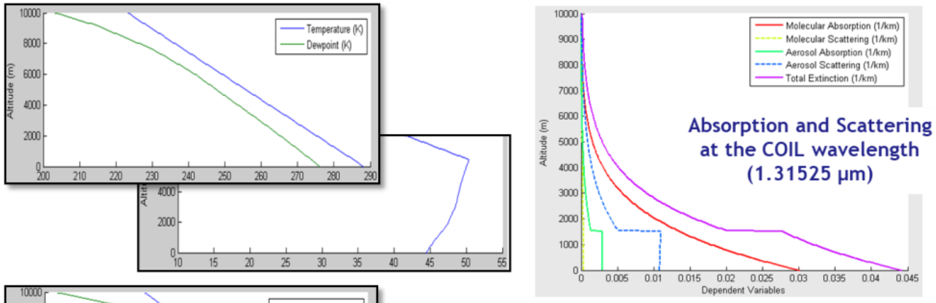
(T=250K)

The Atmosphere

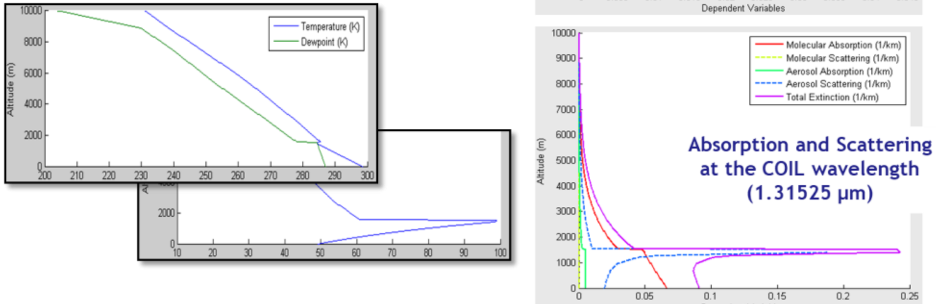
Atmospheric Structure



- US 1976 Standard Atmosphere
- Continental Average Aerosols
- Hufnagel Valley 5/7 C_n^2



Absorption and Scattering at the COIL wavelength (1.31525 μm)



Absorption and Scattering at the COIL wavelength (1.31525 μm)

- ExPERT (Climo) Atmosphere
- Dayton, Ohio
- Climatological C_n^2
- Summer

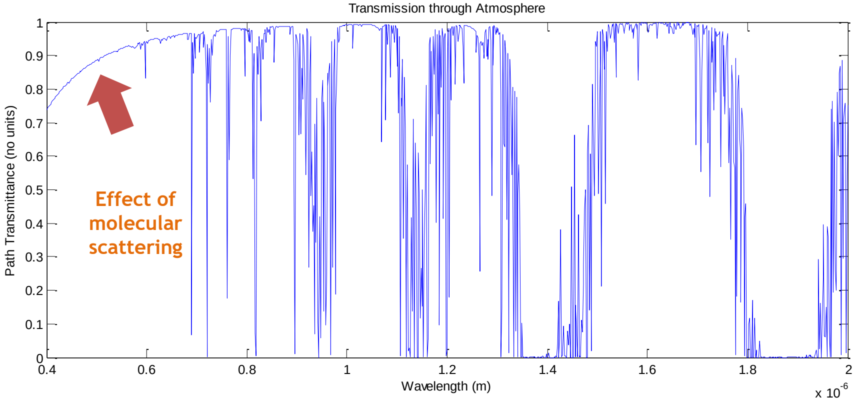
The Atmosphere

Atmospheric Structure

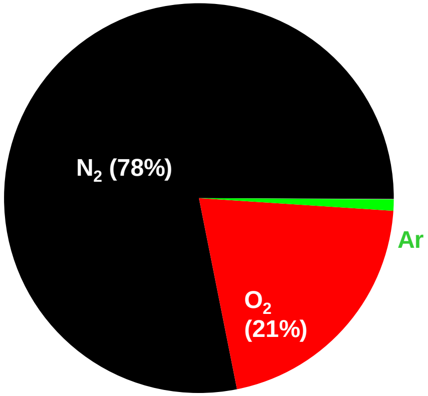
TABLE 2. Molecular absorbers considered in LEEDR.

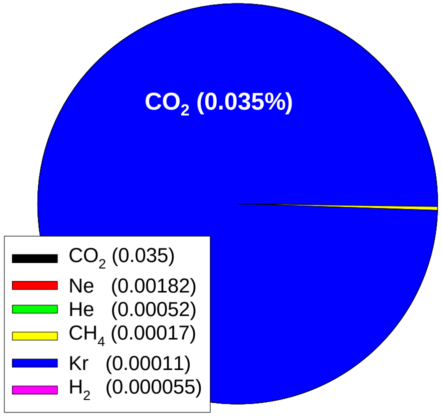
Absorber	Concentration
H_2O (water vapor)	Variable
CO_2 (carbon dioxide)	3.80×10^{-4}
O_3 (tropospheric ozone)	Variable
N_2O (nitrous oxide)	3.20×10^{-7}
CO (carbon monoxide)	1.50×10^{-7}
CH_4 (methane)	1.794×10^{-6}
O_2 (oxygen)	0.209
NO (nitrogen oxide)	2.99×10^{-10}
SO_2 (sulfur dioxide)	2.93×10^{-10}
NO_2 (nitrogen dioxide)	2.99×10^{-11}
NH_3 (nitrogen hydride)	5.03×10^{-11}
HNO_3 (nitric acid)	5.30×10^{-11}

Zenith Transmission
Clear, no aerosols
0.4 to 2.0 µm



Effect of molecular scattering

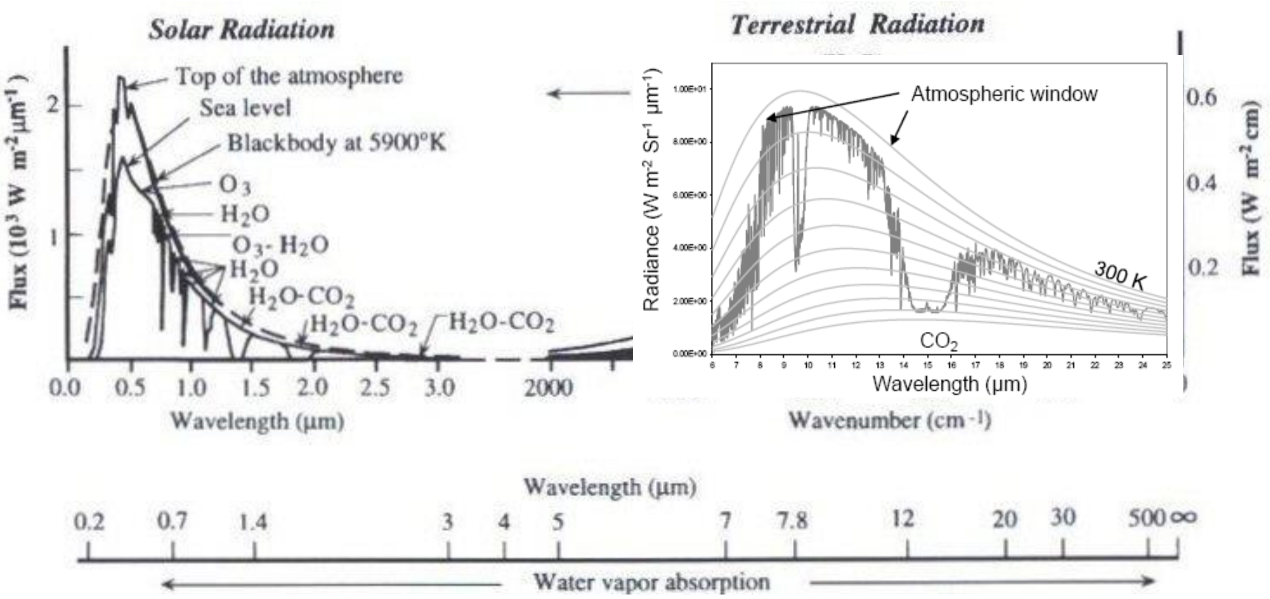




The Atmosphere

Atmospheric Structure

Predominant Absorbers: O_3, H_2O, CO_2

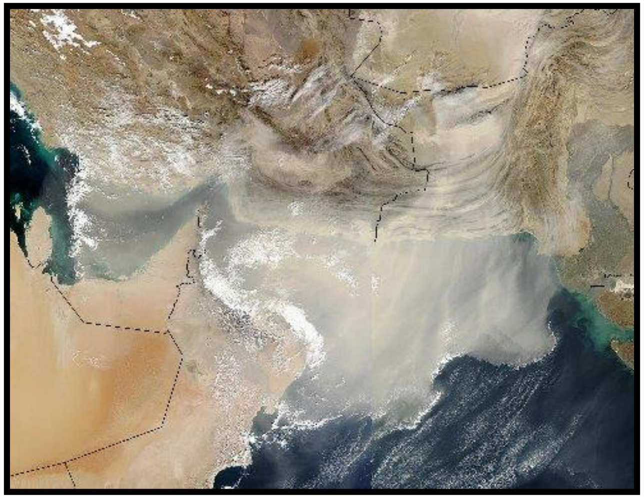


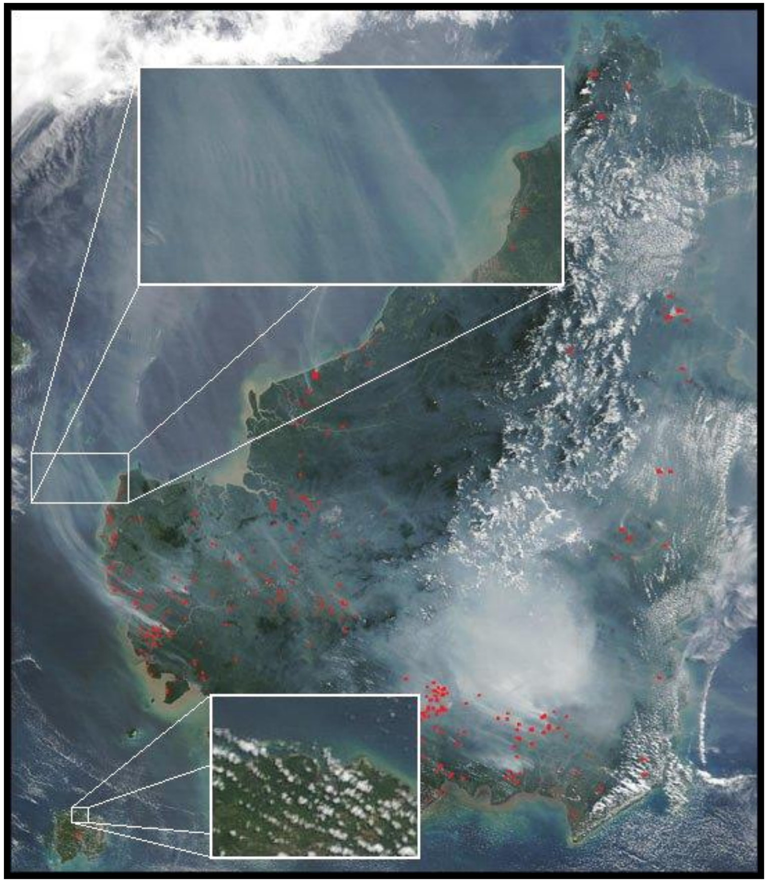
The Atmosphere

Atmospheric Structure

Atmospheric Obstructions

Clouds, Fog, Smoke,
Blowing Snow or Dust



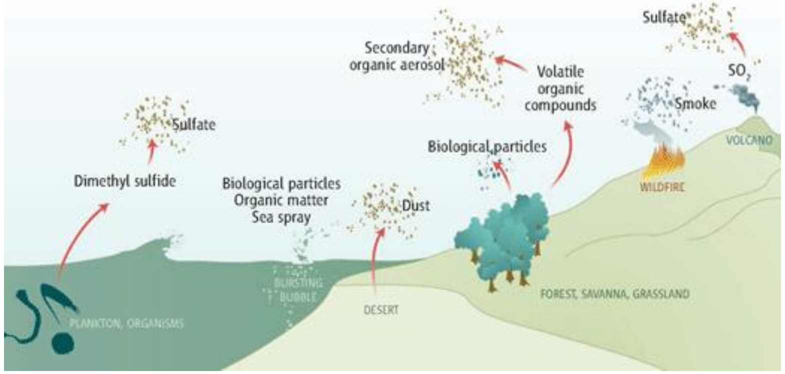


The Atmosphere

Atmospheric Structure

Aerosols (solid or liquid) diameters of 0.005 to 20 microns.

clusters of molecules cloud droplets or sand



KEY PROPERTIES: concentration, mass, size, chemical composition, aerodynamic and optical properties.

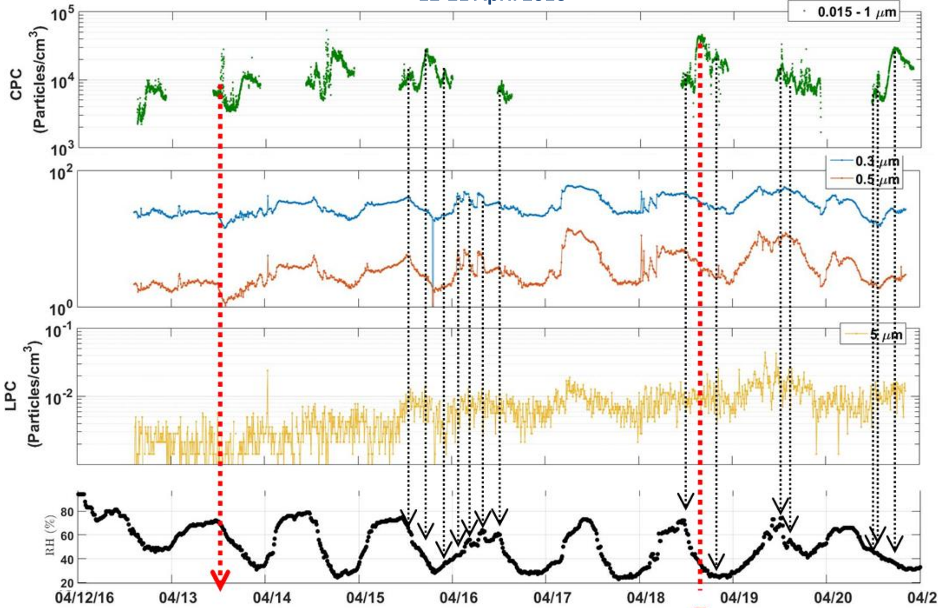
DUSTS: suspension of solids produced by disintegration of materials (d<1µm).

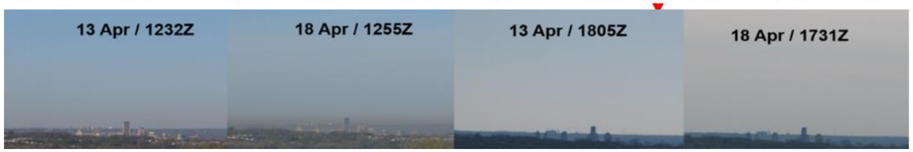
FUMES: solid particles from condensation of previously melted substances.

MISTS/SPRAYS: liquid particles suspended in the air.

SMOKE: small carbon containing particles resulting from incomplete combustion (d>1µm).

Dynamic aerosol loading at WPAFB, OH
12-21 April 2016





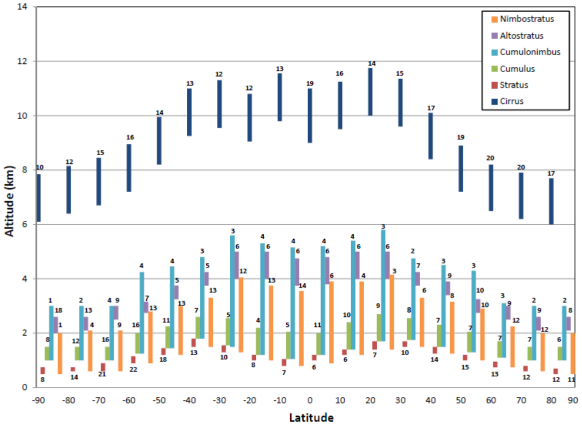
The Atmosphere

Atmospheric Structure

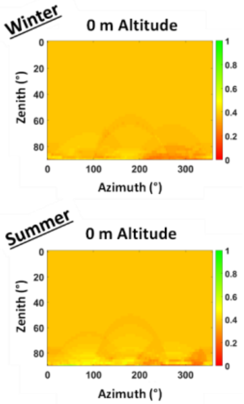
Clouds

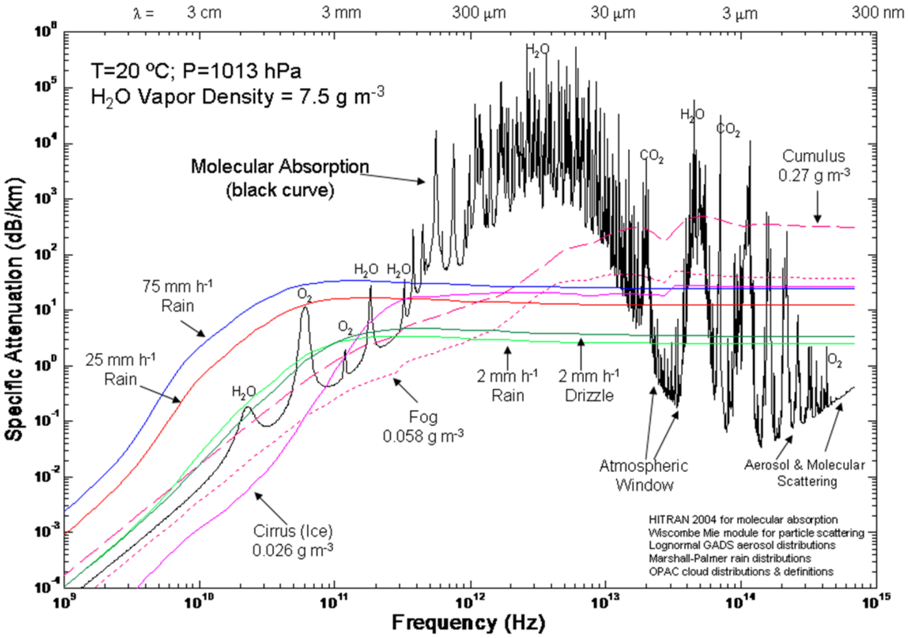
- Consist of small water droplets and ice crystals.
- Average cloud cover is 65% over oceans and 52% over land.
- High altitude clouds consist of ice.
- Middle altitude clouds can be a mixture of water and ice.

-- Photograph by Kevin Knupp --
-- U. of Illinois Cloud Catalog --



Probability of CFLOS
National Capital Region





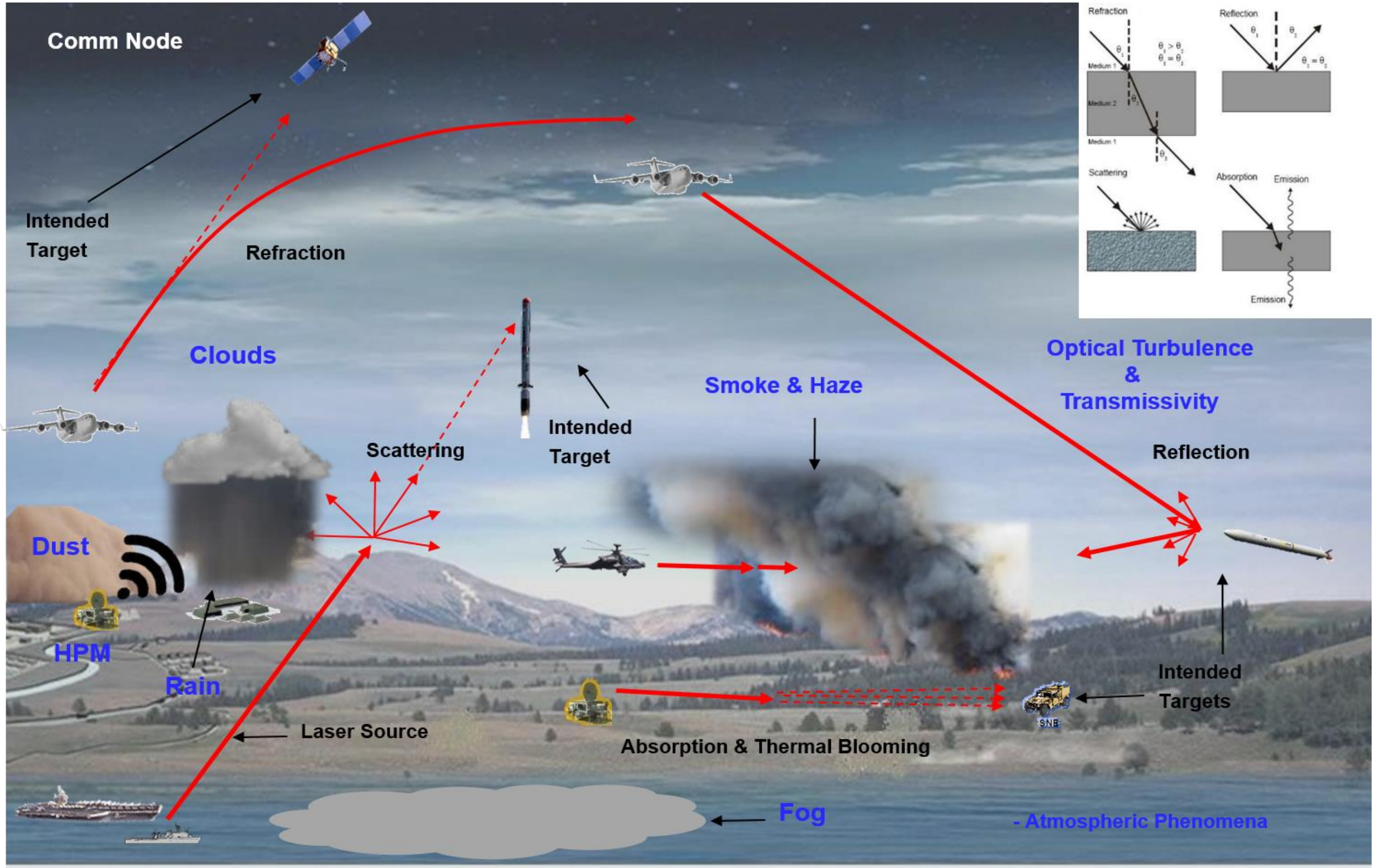
Effect on propagation

- Scatter all wavelengths in the visible spectrum equally.
- Strongly absorb in the Infrared spectrum.

Propagation and Adaptive Optics

6. The Atmosphere
   - 6.1 Atmospheric Structure
   - 6.2 Atmospheric Effects
   - 6.3 Adaptive Optics

Directed Energy Weapons & Weather



Weather Effects Estimator for HEL Performance

Good Day

- Turbulence Low
  - Ocean: Air/Sea temp diff < 2°C
  - Land:
    - near sunrise/sunset

      — and/or —
    - overcast clouds blocking view of sun/moon but not target
- Extinction Low
  - No visibility obstruction

    — or —
  - Low aerosols
    - Blue sky brightness changes when polarized sunglasses are turned 90°
- CFLOS assured
  - No clouds/fog in any possible engagement path

Medium Day

- Turbulence not Low or High
  - Ocean: Air/Sea temp diff -2 to -4°C or +2 to +3°C
  - Land:
    - Engagement path in cloud shadow on partly cloudy day

      — or —
    - Clear night
- Extinction Medium
  - Visibility above 3mi (5km)

    — or —
  - Hazy (sky milky blue)
    - Sky brightness does not change when polarized sunglasses are turned 90°
- CFLOS likely
  - Clouds/fog present but could be avoided for possible engagement paths

Bad Day

- Turbulence High
  - Ocean: Air/Sea temp diff < -4°C or > +3°C
  - Land:
    - Sun above 20° elevation, few or no clouds

      — and/or —
    - Daytime engagement path over pavement or dry surface
- Extinction High
  - Visibility < 3mi (5km)

    — or —
  - Rain > 2mm/hr or Fog or Accumulating Snow
- CFLOS unlikely
  - Clouds/fog not avoidable for most or all possible engagement paths

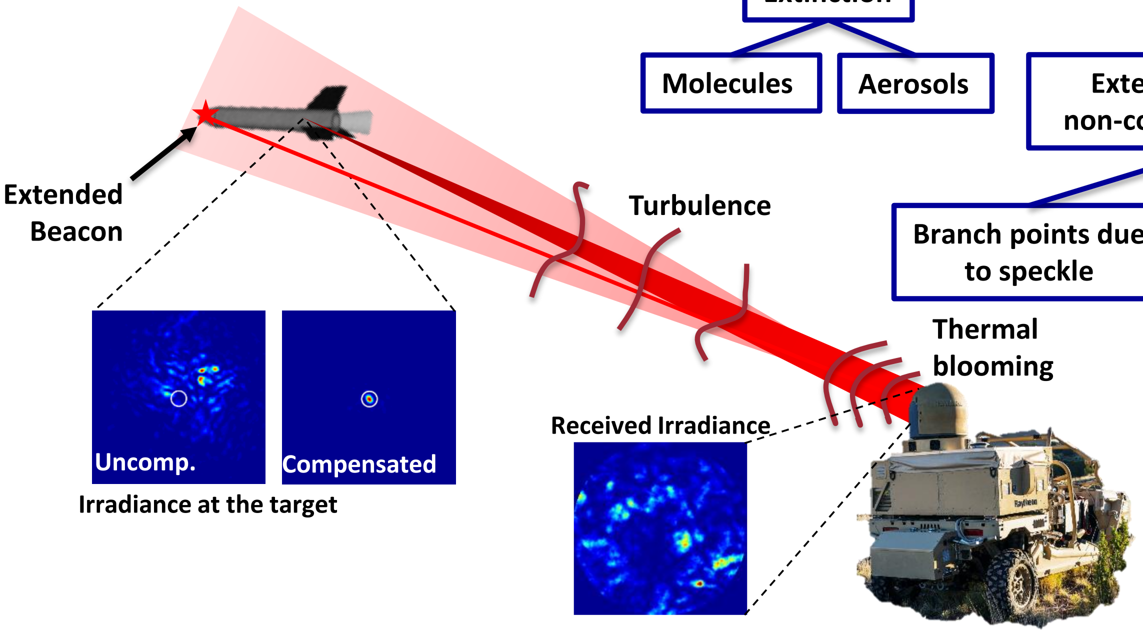
*Optimized for a 1.06µm HEL and a surface-to-surface or surface-to-low-altitude (< 1500m) tactical engagement

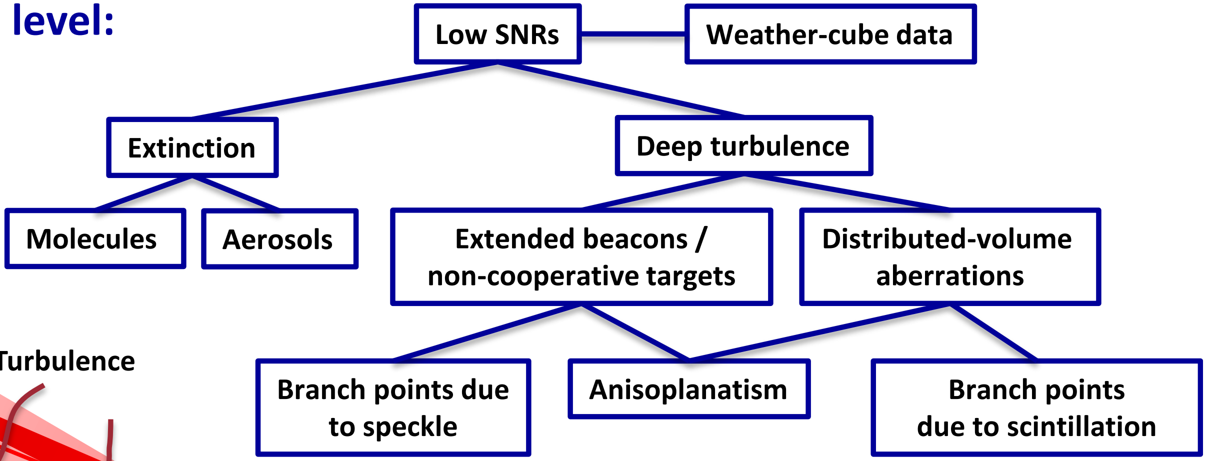
CFLOS: Cloud Free Line of Sight

Weather--particularly turbulence—can significantly degrade HEL performance

Things to consider at the system level:

Low SNRs — lack of photons
SWaP — size, weight, and power
Latency — can you keep up?



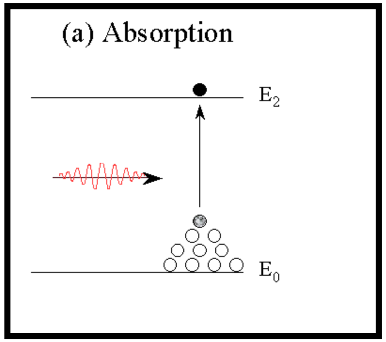


Numerical Weather Modeling enables accurate HEL performance assessment

The Atmosphere

Atmospheric Effects

Absorption: Decreases peak intensity, induces thermal blooming



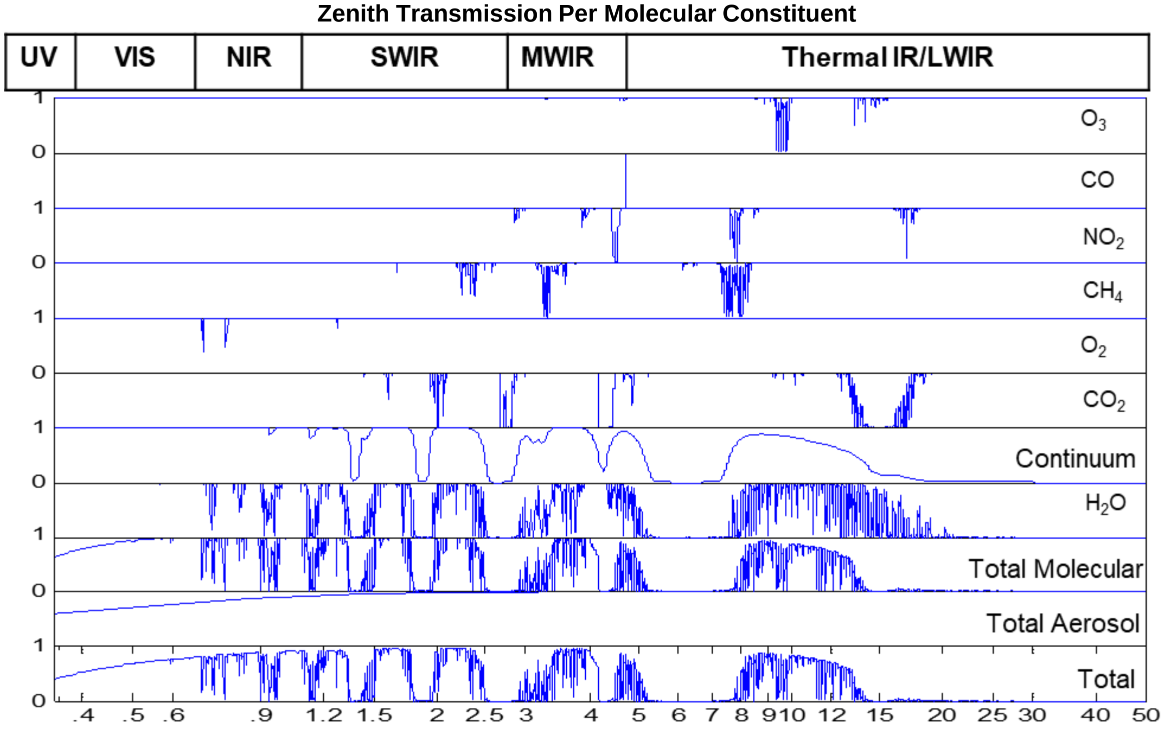
$$\tau = \frac{I_t(\lambda)}{I_o(\lambda)} = e^{-\sigma_{abs}(\lambda) N z}$$

σ_{abs} = cross-section for absorption

N = concentration of absorber

z = propagation length

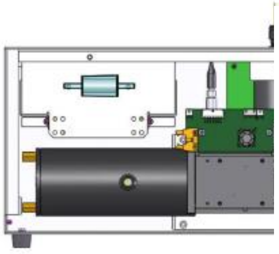
$$\boxed{\alpha_a = \sigma_{asb} N}$$


Zenith Transmission Per Molecular Constituent

Aerosol Extinction (abs + sct) instrumentation

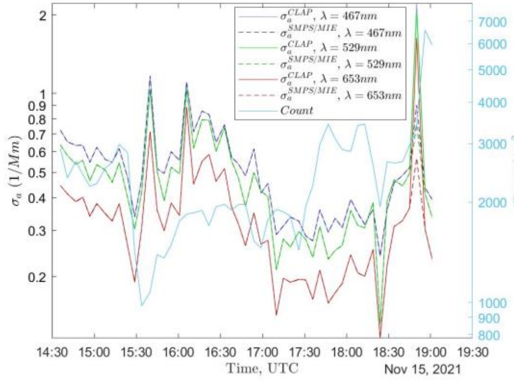
American Ecote

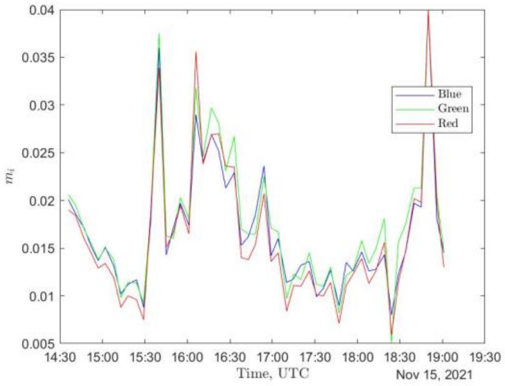
(Aerosol O



λ = 450

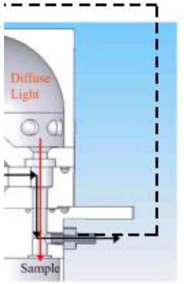
Absorption





s Light Abso

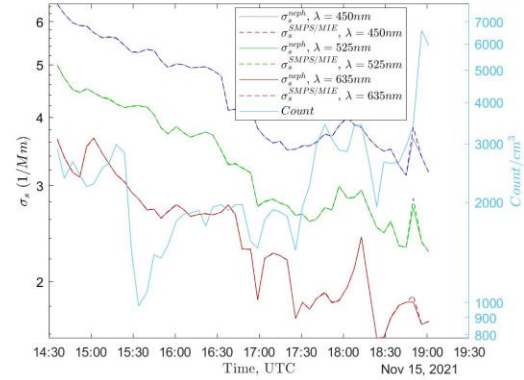
Aerosol Absorpt

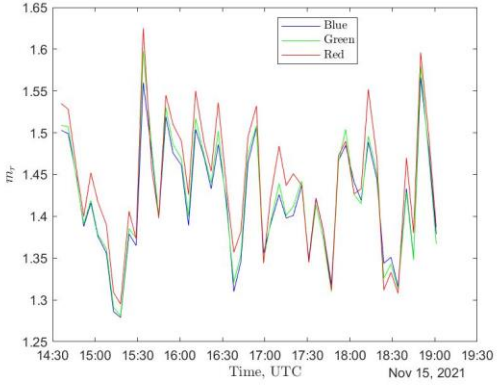


the PSAP, are that it is one-tenth the size, ca
temperature. In addition, the computer softw
applications, and currently NOAA-built CLAP

λ = 467, 529

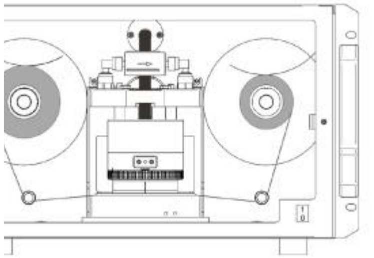
Scattering





c Aethalometer

nitor)



= 370, 470, 520, 590, 660, 880, 950nm

The Atmosphere

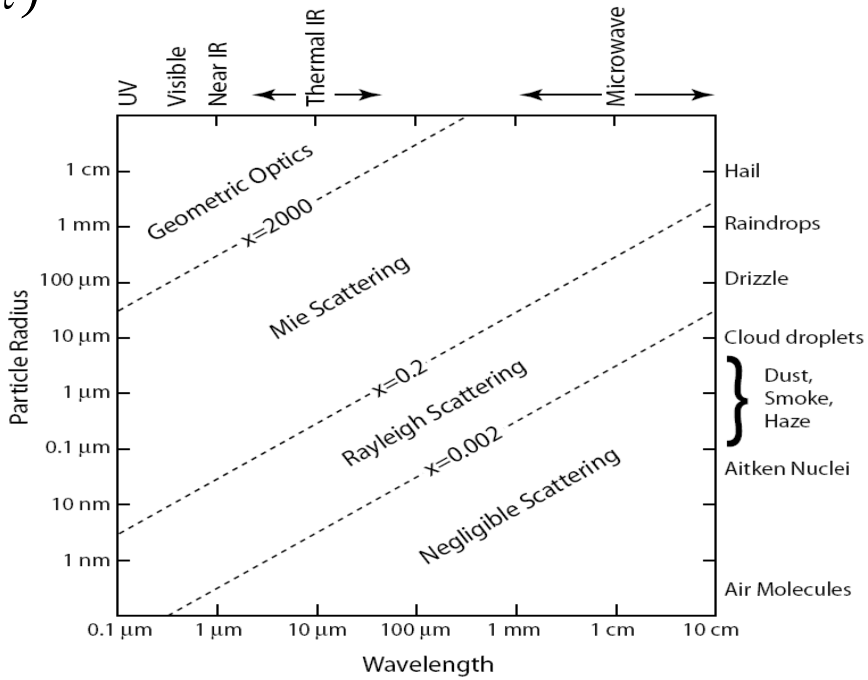
Atmospheric Effects

Scattering: Molecular and aerosol scattering removes intensity from the beam

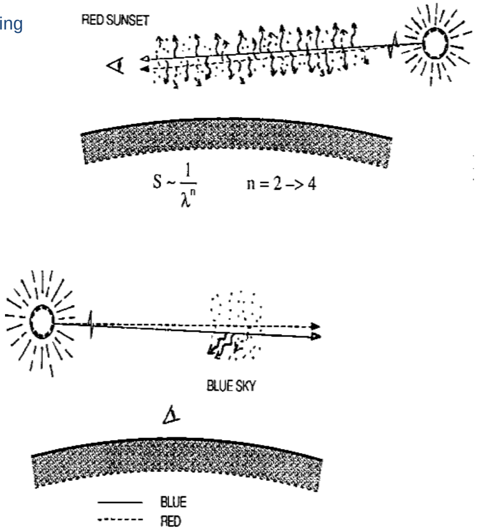
$$\tau_{atmos} = \frac{I_t(\lambda)}{I_o(\lambda)} = e^{-\alpha_s z}$$

α_s= scattering (or extinction) coefficient

z = propagation length



Rayleigh Scattering



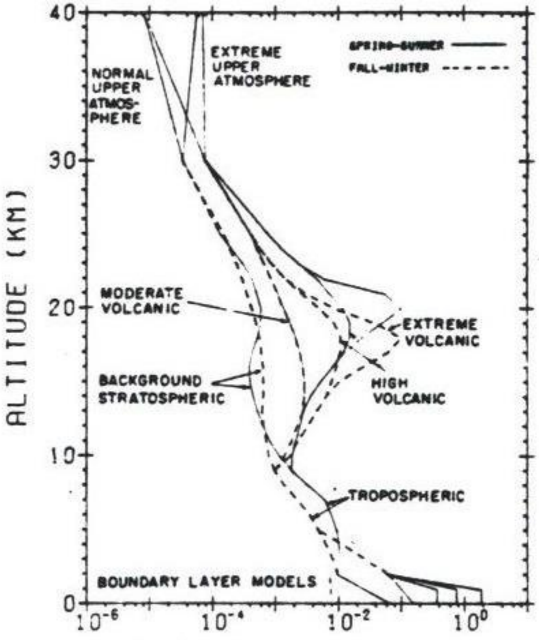
Scattering is reduced at long wavelengths & low particulates/ aerosols

The Atmosphere

Atmospheric Effects

Aerosol Distribution

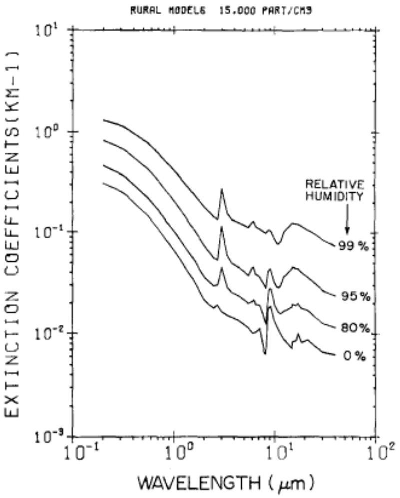
Strongest at the surface. Dust in the stratosphere has a high dwell time.

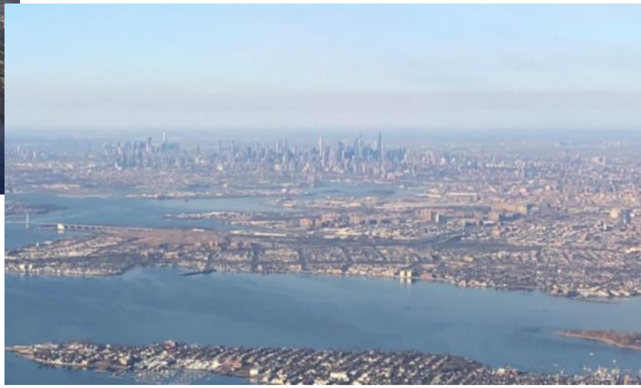


Attenuation Coefficient at 0.55 μm (km^{-1})

Aerosol Extinction

Strongest at short λ. Aerosols absorb water at high humidity yielding more extinction.



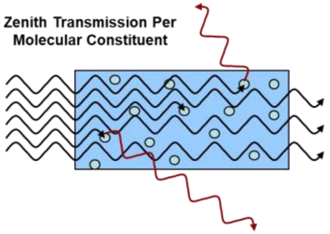


The Atmosphere

Atmospheric Effects

Total attenuation

$$\tau_{atmos} = \frac{I_t}{I_o} = e^{-[\alpha_s(\lambda) + \sum_i \sigma^i{}_{abs}(\lambda) N_i] z}$$



- Beer's Law really only considers absorption in a homogeneous medium:

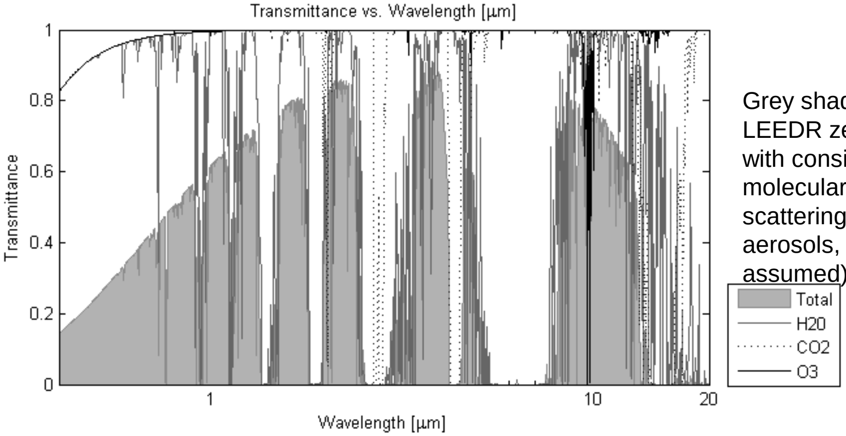
$$I_\lambda(x) = I_{\lambda,0} \exp(-\beta_a x)$$

- Attenuation can be caused by both *absorption* and *scattering*. A general *extinction coefficient* must incorporate both.
- The transmission medium is usually heterogeneous.

$$\boxed{I_\lambda(s_2) = I_\lambda(s_1) \exp\left[-\int_{s_1}^{s_2} \beta_e(s)\, ds\right]}$$

$$\boxed{\tau(s_1, s_2) \equiv \int_{s_1}^{s_2} \beta_e(s)\, ds}$$

$$\boxed{t(s_1, s_2) \equiv e^{-\tau(s_1, s_2)}}$$



Grey shaded area depicts LEEDR zenith transmission with consideration for both molecular and aerosol scattering (cont ave aerosols, 5 km visibility assumed).

Generalization to Arbitrary Mixtures of Components

- The total volume extinction, scattering, and absorbing coefficients for a mixture are equal to the sums of the corresponding coefficients for the individual components.

$$\beta_e = \sum_i \beta_{e,i} = \sum_i \rho_i k_{e,i} = \sum_i N_i \sigma_{e,i}$$

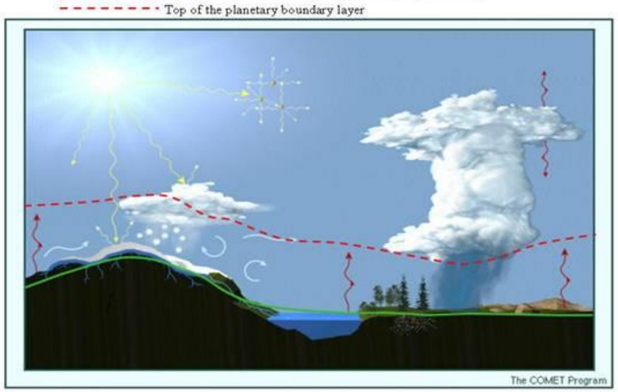
$$\beta_a = \sum_i \beta_{a,i} = \sum_i \rho_i k_{a,i} = \sum_i N_i \sigma_{a,i}$$

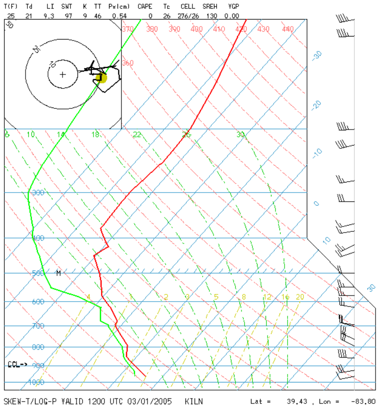
$$\beta_s = \sum_i \beta_{s,i} = \sum_i \rho_i k_{s,i} = \sum_i N_i \sigma_{s,i}$$

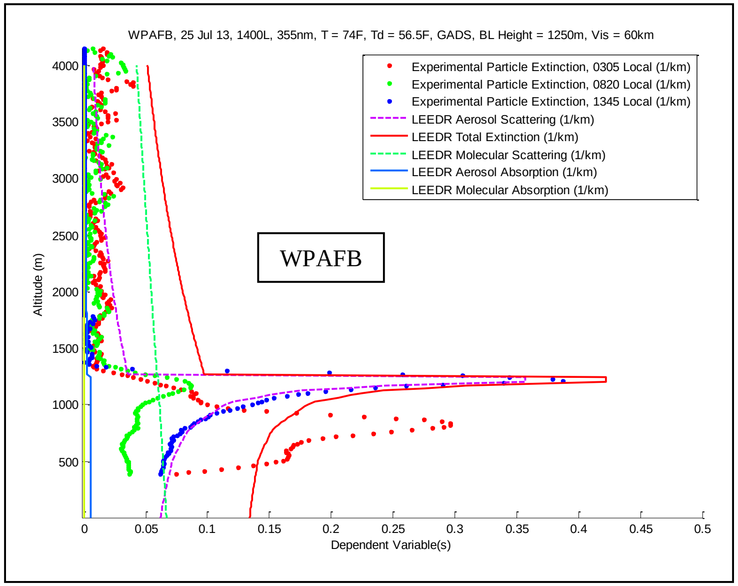
The Atmosphere

Atmospheric Effects

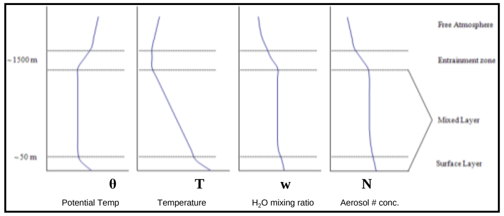
Depiction of various surfaces and PBL processes





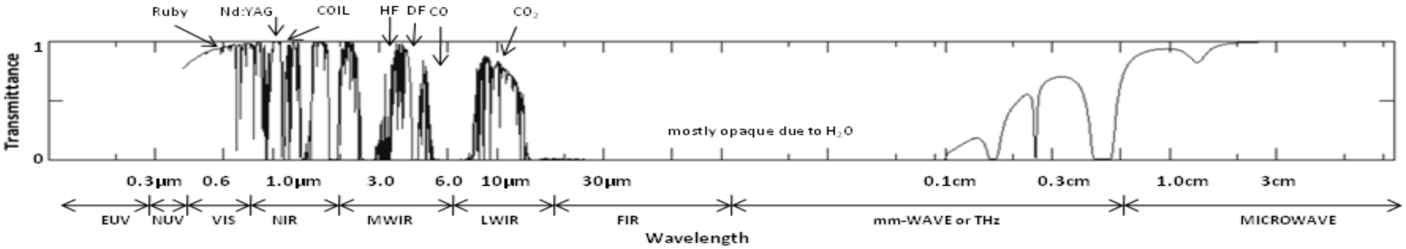


- Atmospheric Boundary Layer
  - Well mixed layer up to 1.5-2.0 km thick
  - Capped by temperature inversion
- Boundary Layer Effects
  - Trap pollutants & aerosols
  - Location of wind shear
  - Atmospheric turbulence (surface layer)
  - Increasing RH & extinction with height



The Atmosphere

Atmospheric Effects



The Moderate Resolution Transmittance (MODTRAN) Code calculates atmospheric transmittance and radiance for frequencies from 0 to 50,000 cm^{-1} at moderate spectral resolution, primarily 0.2 to 1 cm^{-1} (MODTRAN 6.0 version now at 0.1 cm^{-1})

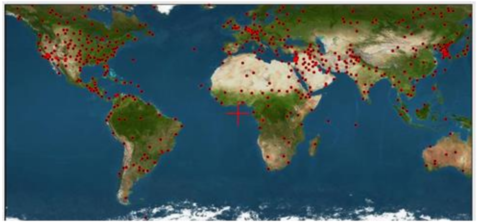
HITRAN (high-resolution transmission molecular absorption database) is a compilation of spectroscopic parameters that a variety of computer codes use to predict and simulate the transmission and emission of light in the atmosphere.

The Fast Atmospheric Signature Code is a first principles, line-by-line atmospheric radiance and transmittance code. FASCODE was the standard benchmark for atmospheric background codes based on band models for radiation transport.

The Laser Environmental Effects Definition and Reference (LEEDR) is an AFIT line-by-line (or 1 cm^{-1} band model) atmospheric characterization code that captures effects for λ's = 200 nm to 8.6 m

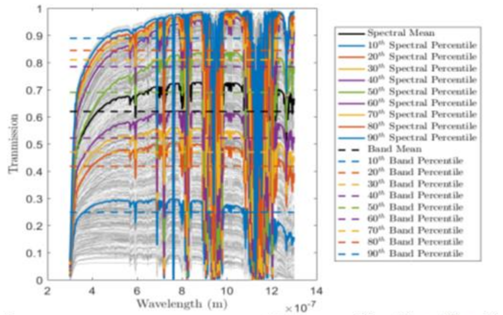
The Atmosphere

Atmospheric Effects: Laser Environmental Effects Definition and Reference



573 ExPERT (land) locations represented in LEEDR

Worldwide climatology for diffuse cloud transmission

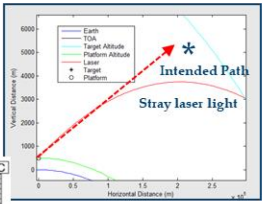


V&V'd Atmospheric Effects and Radiative Transfer Code for HEL

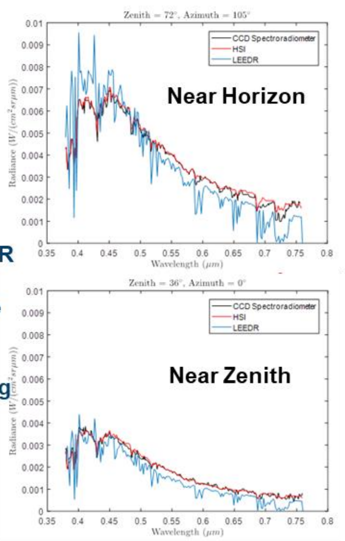
Creates physically realizable horizontal / vertical profiles of meteorological and weather event data and associated radiative effects (e.g. optical extinction, path radiance):

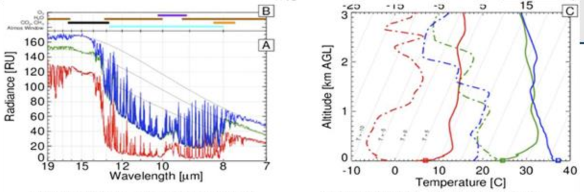
- **Aerosol and surface observation (i.e. T, P, RH) climatology at 573 ExPERT and 1° x 1° oceanic grid locations**
- **Numerical weather forecast, re-analysis data**
- **Profiles optical turbulence (i.e. C_n^2)**
- **Accounts for light-refraction and single/multi-scatter**
- **Includes sun-moon calculator**

Light Refraction: Path Bending



UV/VIS/NIR Path Radiance with Multiple Scattering



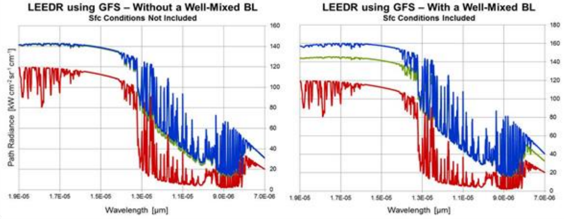


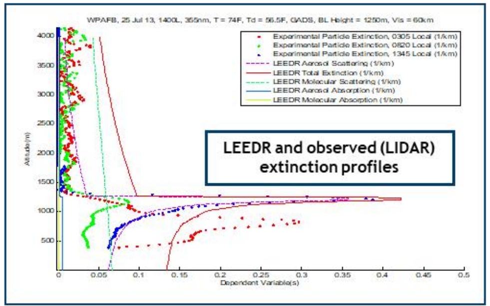
LWIR Path Radiance

Red: 7 Nov 2012 at 1125Z

Green: 27 June 2013 at 1132Z

Blue: 27 June 2013 at 1731Z





LEEDR and observed (LIDAR) extinction profiles

A tool for Applied Physics, Nuclear Physics, Atmospheric Physics, Remote Sensing, & DE

The Atmosphere

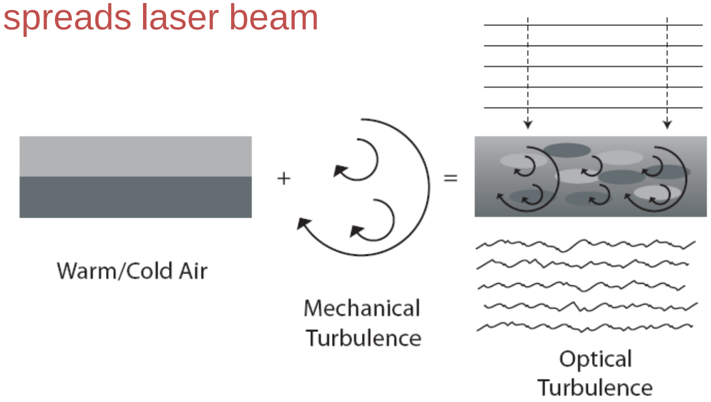
Atmospheric Effects

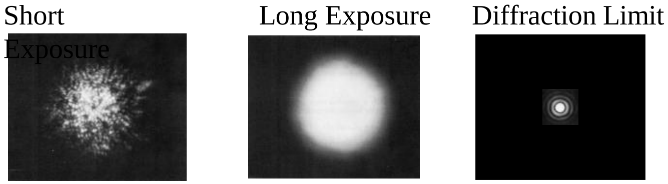
Turbulence: Historical perspective

- **1600’s:** With Galileo’s telescope and diffraction experiments by Huygens, Fresnel and others, it was shown that the spread of stars was much broader (lower resolution) than expected from laboratory
- **1717:** Newton first conjectures that this difference is due to the atmosphere
- Until 1950’s little more than characterizing these effects (versus understanding) was accomplished
- **1958:** Rosch and short exposure images – “Bunch of grapes”
- **1961:** Kolmogorov publishes treatise on spatial statistics of turbulent flow
- **1961:** Tatarski uses Kolmogorov’s model to develop theory of E-M wave propagation through turbulent media
- **1966:** Fried uses Tatarski’s results to explain the difference between short and long exposure imagery and derives a single parameter, r_0 for describing the effects of turbulence on resolution

- These works laid the theoretical foundation for all future work

Turbulence: Turbulent atmosphere distorts and spreads laser beam





The Atmosphere

Atmospheric Effects

Fluid flow or air flow is characterized as laminar or turbulent

At low velocity, the fluid flow is regular and smooth, or laminar.
At higher velocity, the fluid is unstable and random, or turbulent.

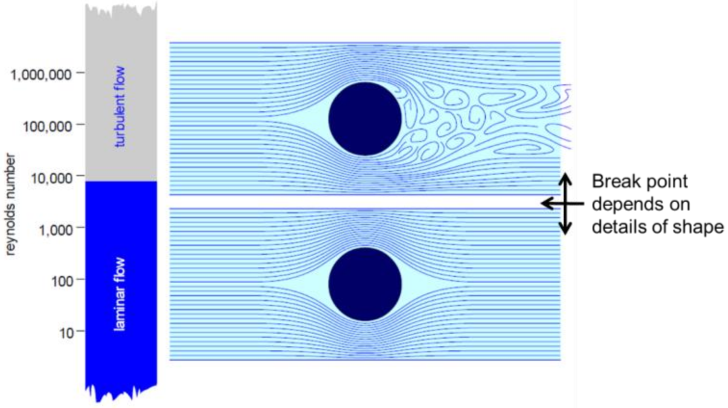
The transition between laminar and turbulent flow is defined by the Reynolds Number:

Laminar: $Re < 2000$

Turbulent: $Re > 3000$

$$Re = \frac{vL}{\mu/\rho}$$

v = flow velocity
L =characteristic length
μ = viscosity
ρ = density



Turbulence is flow regime characterized by random fluctuations of the flow properties – velocity, temperature, density.

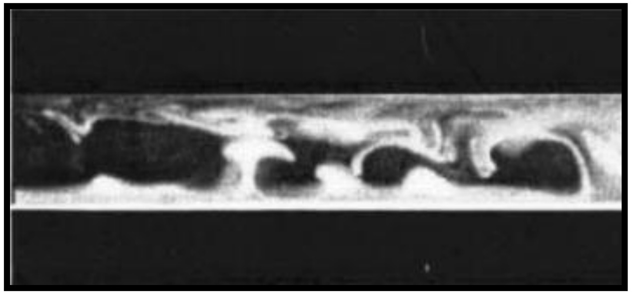
In air ($\mu/\rho = 1.5 \times 10^{-5}$ m^2/s) and for L=10 m and v = 1 m/s → $Re = 6.7 \times 10^5$

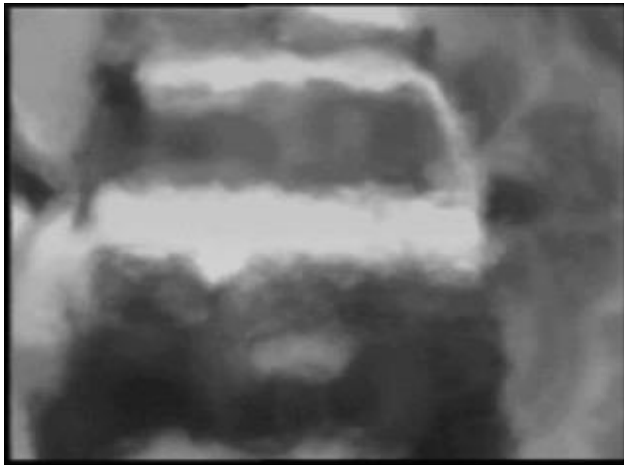
Thus, the atmosphere is turbulent at all but very small distances

The Atmosphere

Atmospheric Effects

- Turbulence
  - Irregular or random motions in a fluid
- Sources of Turbulence
  - Convection from hot surfaces
  - Wind shear
  - Weather systems
  - Laser heating (thermal blooming)
- Effects of Turbulence
  - Variations in air temperature and composition
  - Changes the index of refraction
  - Changes the light as it propagation

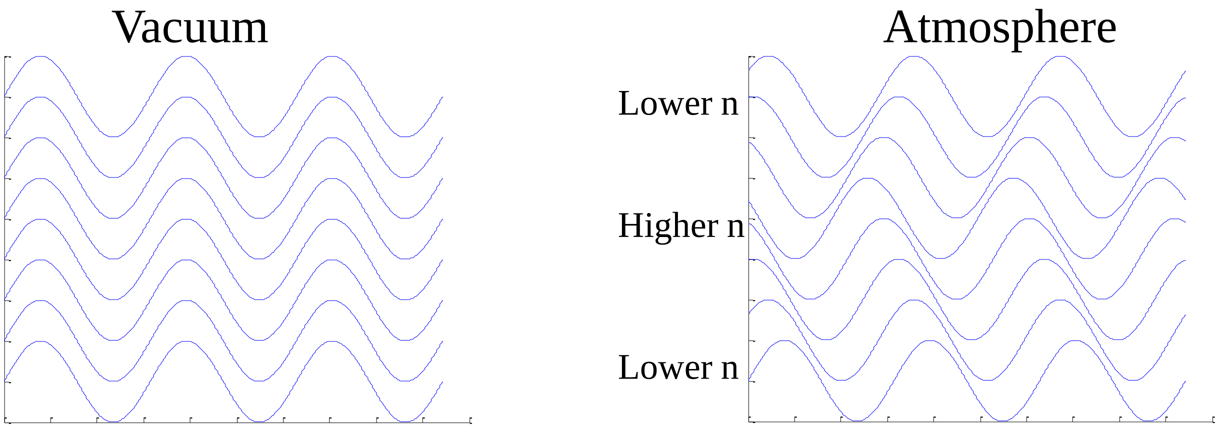




The Atmosphere

Atmospheric Effects

- Variations in temperature cause change in the index of refraction
  - Thus the light will have different ‘optical distances’ to travel
  - This leads to a change in the phase of the light
  - Phase aberrations, when propagating through space, lead to changes in intensity of beam



Note: A lower n implies a faster speed

The Atmosphere

Atmospheric Effects

- Turbulence in the atmosphere randomizes the temperature distribution of the air.
- Index of refraction of air is quite sensitive to temperature:

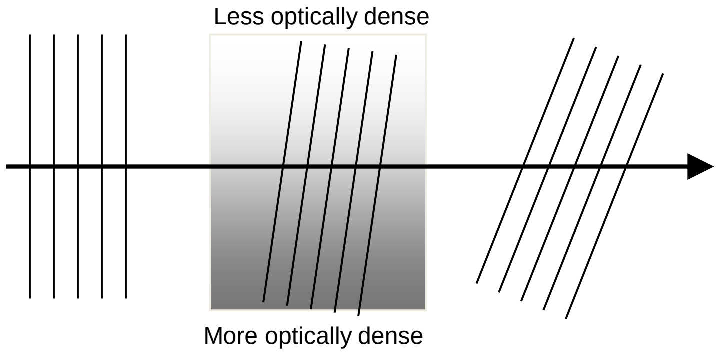
$$n = 1 + 77.6\left(1 + 7.52 \times 10^{-3}\lambda^{-2}\right)\frac{P}{T} \times 10^{-6},\ \text{P in millibars, T in Kelvins, } \lambda = \text{wavelength in microns}$$

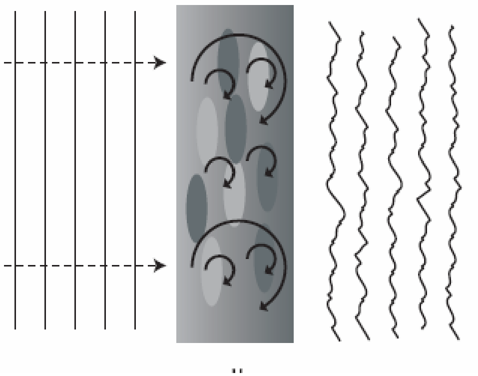
- In a turbulent flow, the pressure and temperature are random processes in space and time, and hence the index of refraction is also random in space and time.
- It is customary to represent the random component of the index of refraction of air using n_1, so that we may write $n_1 = n - 1$. (Ignoring the fact $n \approx 1.0003$ and not 1. n=1+N+n_1)
- These index of refraction fluctuations may, at first, seem very weak. However, the optical path length of a light ray passing through such a medium with propagation in the z-direction, with (x,y) representing coordinates in a receiving aperture. is given by: $$OPL(x,y) = \int_{path} n(x,y,z)\,\mathrm{dz}$$
- The associated phase error (i.e., aberration) in the aperture is: $$\phi(x,y) = \frac{2\pi}{\lambda} OPL(x,y)$$
- Thus small changes in OPL can cause big changes in phase. Further, if the scale of the fluctuations in the (x,y) plane is smaller than the receiving aperture, we would expect to experience the effects of random aberrations.

The Atmosphere

Atmospheric Effects

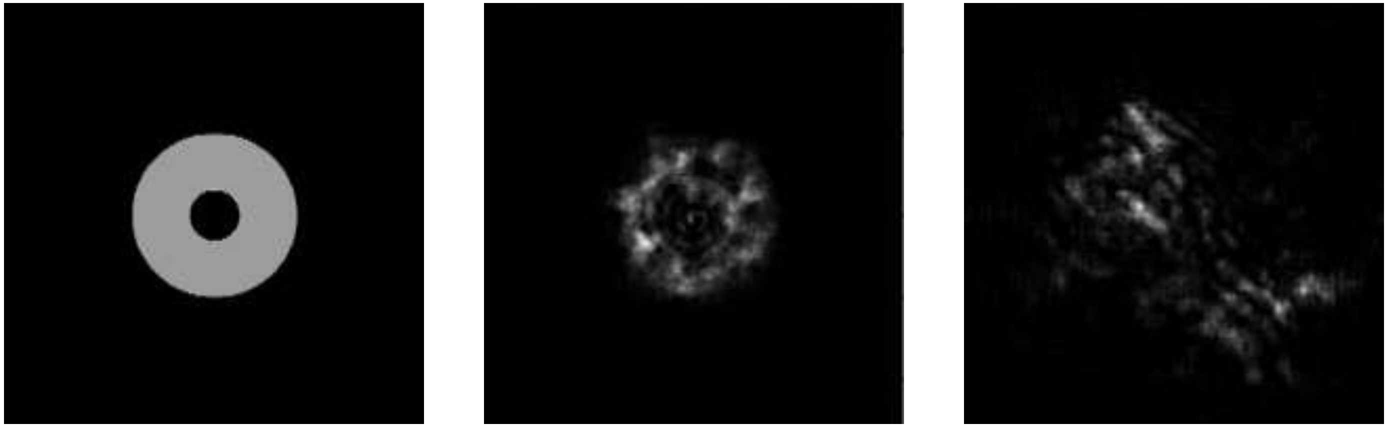
- Usually, the light is represented pictorially by the wavefront, i.e. the line joining part of the electromagnetic wave with equal phase.
- Non-planar wavefronts are called optical aberrations





The Atmosphere

Atmospheric Effects



Simulated intensity of a beam coming out of a Cassegrain-aperture, going through 5km of strong optical turbulence. The picture on the left is the intensity directly after the transmitter-telescope, in the middle after 1km and on the right after 5km. The represented field is 0.512m x 0.512m, the aperture has an outer diameter of 20cm and an inner obscuration of 6cm diameter, wavelength is 1.064µm

The Atmosphere

Atmospheric Effects

Assume turbulence is isotropic, homogeneous, and ergodic.

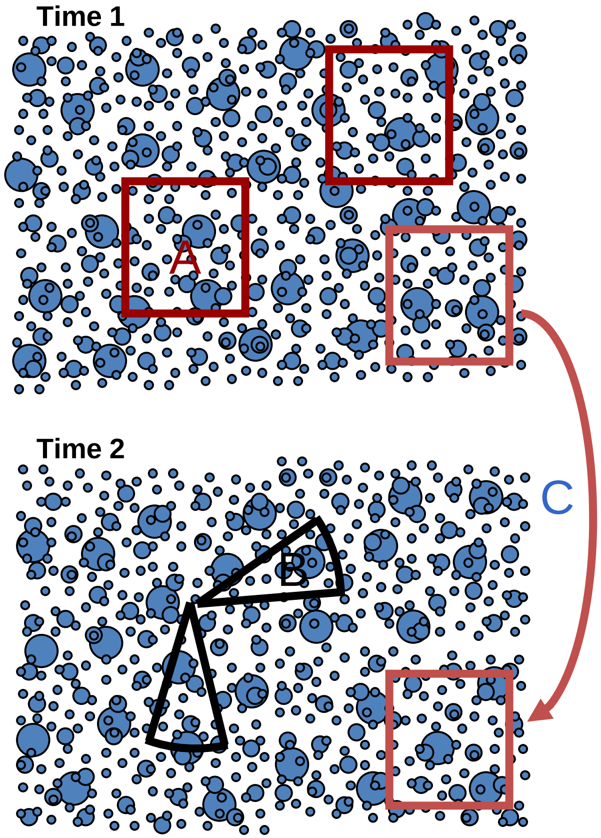
The statistical behavior remains constant, even with changes in:

- Position (homogeneous) (A)
- Direction (isotropic) (B)
- Time (ergodic) (C)

Ergodic: All accessible states equally probable over a long period of time.

Isotopic: Independent of direction

Homogeneous: Same throughout, independent of location



The Atmosphere

Atmospheric Effects

ADDITIONAL INFORMATION

Temperature variations are the primary source of index variations:

$$n(T)-1=\left[n(15^{o}C)-1\right]\left[\frac{1.059}{1+\left(0.00366\ {}^{o}C^{-1}\right)T}\right]$$

$$\frac{dn}{dT}\cong 10^{-6}\ {}^{o}C^{-1}$$

In the 360 to 3000 nm range, there are also water vapor + CO$_2$ effects and a small wavelength dependence:

$$(n-1)\times 10^{-6}=M_1(\lambda)\frac{P}{T}+4.615\left(M_2(\lambda)-M_1(\lambda)\right)Q$$

$$M_1(\lambda)=23.7134+\frac{6839.397}{130-\sigma^2}+\frac{45.473}{38.9-\sigma^2}$$

$$\sigma = 1/\lambda$$

$$M_2(\lambda)=64.8731+.58058\sigma^2-.0071150\sigma^4+.0008851\sigma^8$$

The mean square difference in the index of refraction at points separated by a distance r, is termed the structure function:

$$D_n(\vec{r}_1,\vec{r}_2)=D_n(r)=\left\langle\left|n(r_1)-n(r_1+r)\right|^2\right\rangle$$

Similarly for phase (which defines impact from atmosphere):

$$D_\phi(\vec{r}_1,\vec{r}_2)=D_\phi(r)=\left\langle\left|\phi(r_1)-\phi(r_1+r)\right|^2\right\rangle$$

The Atmosphere

Atmospheric Effects

Kolmogorov's theory establishes a structure function for the atmosphere:

$$D_n(r) = \begin{cases} C_n^2 r^{2/3} & l_0 < r < L_0 \\ C_n^2 l_0^{-4/3} r^{2/3} & r < l_0 \end{cases}$$

in terms of a structure constant, C_n^2, which measures the strength of atmospheric turbulence:

$C_n^2 \sim 10^{-17}\ m^{-2/3}$ is 'weak' turbulence
$C_n^2 \sim 10^{-13}\ m^{-2/3}$ is 'strong' turbulence

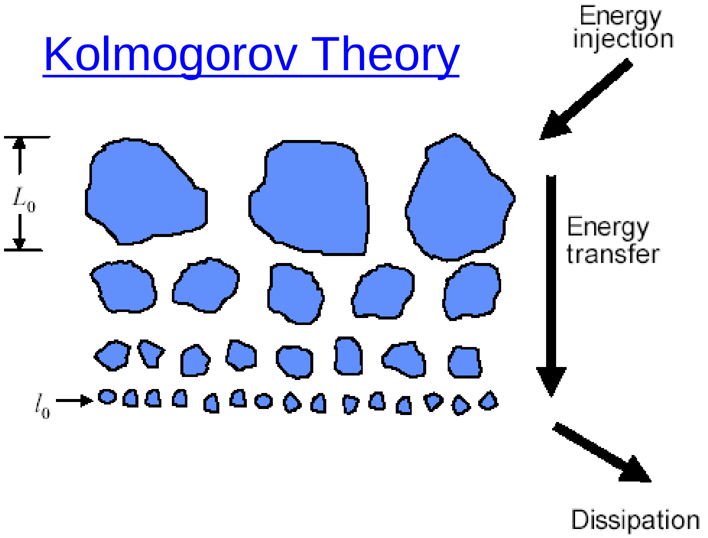
Andrei Nikolaevich Kolmogorov
April 25, 1903 - October 20, 1987

The index of refraction structure function constant, C_n^2, varies in both time and space. Its has been measured at several sites and parametric expressions are available. The Fourier Transform of the structure function of the refractive index leads to the Kolmogorov 3-D Power Spectrum.

The Atmosphere

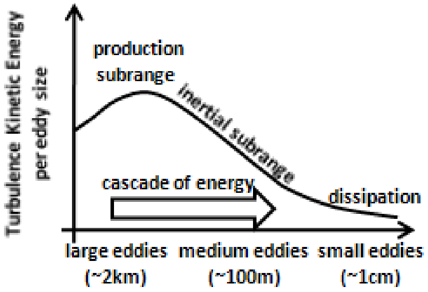
Atmospheric Effects

Kolmogorov Theory



L_o = outer scale ≅ 10’s – 100’s m

non-homogeneous



l_o = inner scale ≅ 0.1 - 10 mm

homogeneous / isotropic

Kolmogorov was working in fluids, his theory was adopted by Tatarski and Obukrov to atmospherics. Kolmogorov applied intuition (later verified through lab measurements) and an argument based on conservation of energy that fluctuations in the spatial cells depended on kinetic energy rate per unit mass and distance. Cascading through the inertial region, eventually, this energy is dissipated, where,

$$\boxed{{}^{\mathrm{v}^3}\!/_{\mathrm{L}} \propto \varepsilon \Rightarrow \mathrm{v} \propto (\varepsilon \mathrm{L})^{1/3} \Rightarrow \mathrm{C}_\mathrm{v}^2 \mathrm{R}^{2/3}}$$

The Atmosphere

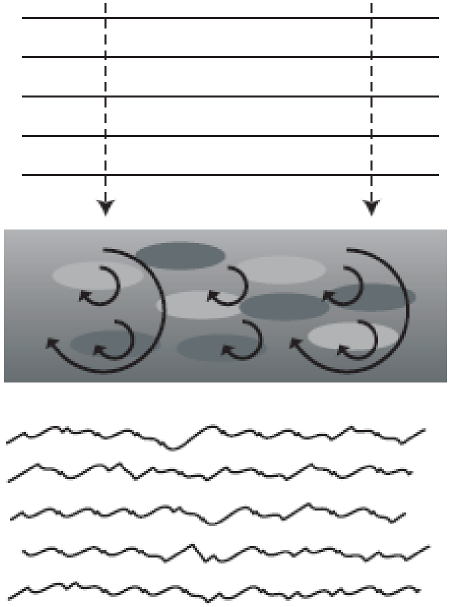
Atmospheric Effects

- Massive data gathering campaigns have resulted in some standard turbulence strength as a function of altitude profiles we will present next.
- These profiles do not come with any statement about the uncertainty in any of the coefficients, even though they must have been developed from a large number of quite noisy observations.
- As a result, standard practice today is to establish a mean profile, a worst case profile, and a best case profile, and run the performance models for these cases.
- The index of refraction structure function constant, C_n^2, varies in both time and space. Its has been measured at several sites and parametric expressions are available and will be discussed next. In general, the turbulence can be categorized as:

$C_n^2 \sim 10^{-17}\ m^{-2/3}$ is 'weak' turbulence
$C_n^2 \sim 10^{-13}\ m^{-2/3}$ is 'strong' turbulence

- Using Kolmogorov's result, the effect on phase can be written as below, which is dependent on the path integrated (summed) C_n^2 along the entire path or propagation:

$$D_\phi(r) = 2.91 k^2 r^{5/3} \int C_n^2 dz$$



The Atmosphere

Atmospheric Effects

Hufnagel-Valley (HV)

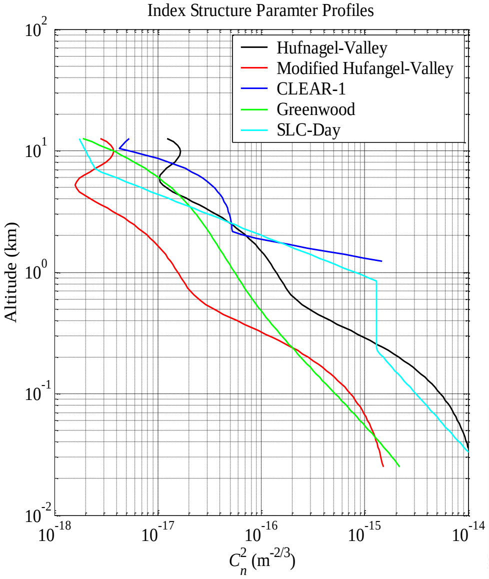
$$C_n^2(h) = 5.94\times10^{-53}\left(\frac{W}{27}\right)^2 h^{10} e^{-h/1000} + 2.7\times10^{-16} e^{-h/1500} + Ae^{-h/100}$$

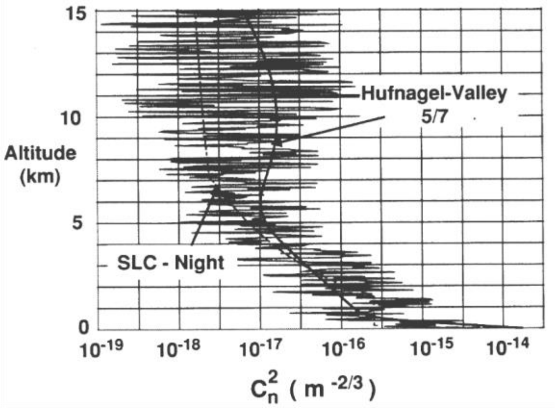
Parameters used

- Strength of surface turbulence, *A*
- Speed of high altitude winds, *v*
- Typical values

$$A = C_n^2(h=0) = 1.7\times10^{-14} m^{-2/3}$$

$$W = rms\ wind\ speed = 21\, m/s$$





The Atmosphere

Atmospheric Effects

wind speed often modeled by

$$w = \left[\frac{1}{15\times 10^3} \int_{5\times 10^3}^{20\times 10^3} \left\{ \omega_s h + w_g + 30 \exp\left[-\left(\frac{h-9400}{4800} \right)^2 \right] \right\}^2 dh \right]^{1/2} .$$

Here, w_g is the ground wind speed and ω_s is the beam **slew rate**.

The Bufton wind speed is often used:

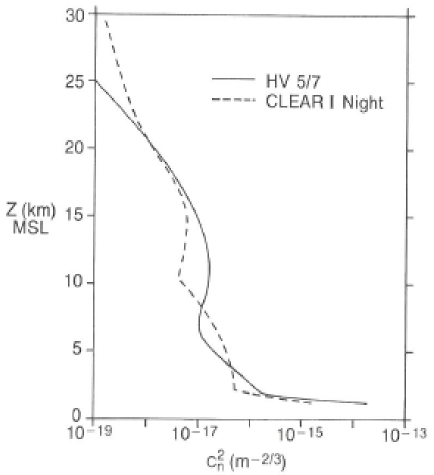
$$v(m/s) = 5 + 30\, exp\left\{ -\left[\left(h - 9400m \right) / 4800m \right]^2 \right\}$$

The Atmosphere

Atmospheric Effects

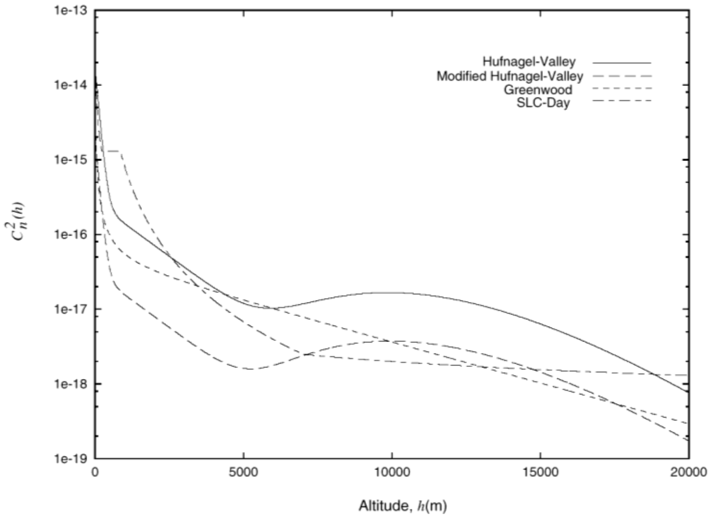
Clear 1:

$$\log_{10} C_n^2 = \begin{cases} C_n^2 = 0 & h < 1.23 \text{ km} \\ -10.7025 - 4.3507h + 0.8141h^2 & 1.23 < h < 2.13 \text{ km} \\ -16.2897 + 0.0335h - 0.0134h^2 & 2.13 < h < 10.34 \text{ km} \\ -17.0577 - 0.0449h - 0.0005h^2 + 0.6181e^{-.5\left(\frac{h-15.5617}{3.466}\right)^2} & 10.34 < h < 30 \text{ km} \end{cases}$$



Greenwood:

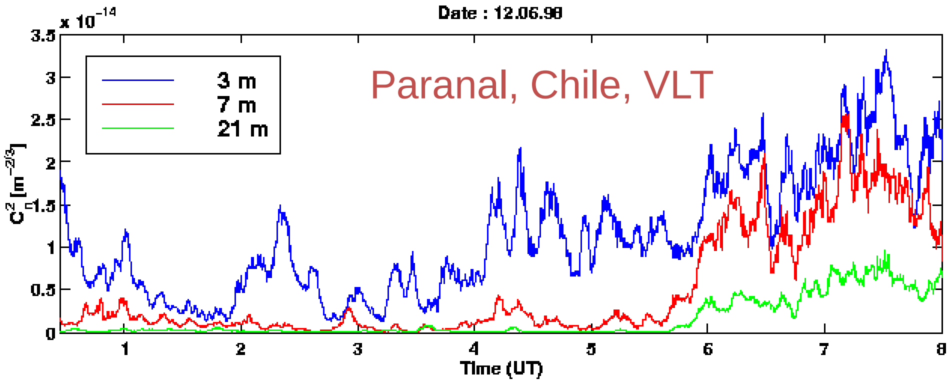
$$C_n^2 = \left[2.2x10^{-13}(h+10)^{-1.3} + 4.3x10^{-17}\right] exp\left\{-\frac{h}{4000}\right\}$$



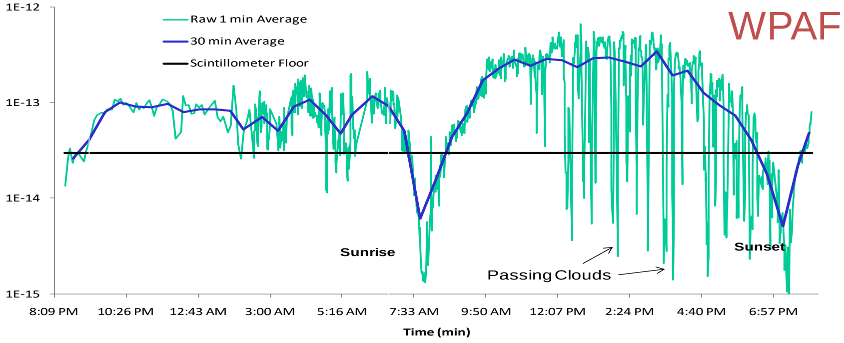
The Atmosphere

Atmospheric Effects

Optical Turbulence is highly variable with date, time, location, altitude, and weather phenomena.



Paranal, Chile, VLT



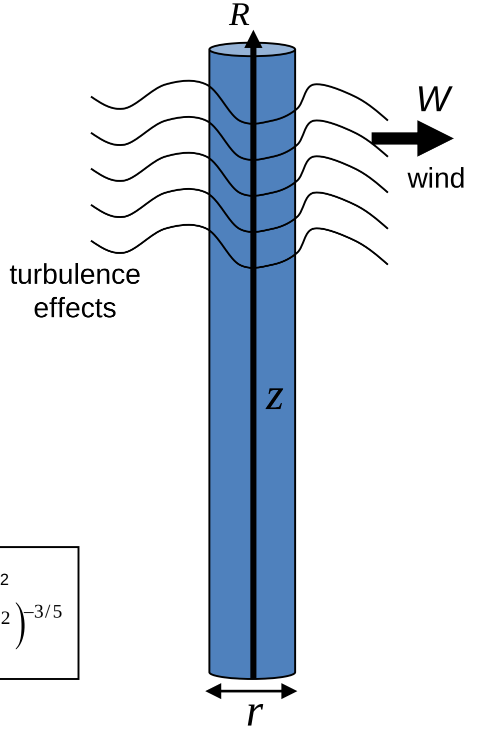
WPAFB OH Sep 08

The Atmosphere

Atmospheric Effects

Fried Coherence Length, r_o, for plane wave,

A convenient measure of the strength of turbulence, as it represents the integrated effect of the refractive-index fluctuations along the path of interest. Small values of r_o correspond to strong turbulence and poor seeing, while large values mean weak turbulence and good seeing. r_o is roughly the radius of a circle within which the phase does not change significantly (RMS difference of 1 radian). If the aperture is less than r_o, AO is of little value.



$$r_o = \left[\frac{2.905}{6.88} \left(\frac{2\pi}{\lambda} \right)^2 \int_{path}^{R} C_n^2(h(z))dz \right]^{-3/5}$$

For constant C_n^2

$$r_o = 1.68\left(C_n^2 R k^2\right)^{-3/5}$$

r_o = 1 – 10 cm (tactical), 0.1 – 1 m (strategic)

The Atmosphere

Atmospheric Effects

Fried Coherence Length, r_o, for spherical wave

Another definition of r_o commonly found in the literature is that for a spherical wave. This would be considered for use analyzing potential performance of a system that is focusing the projected beam to a target. Note that the kernel of the integral is modified to account for the reduced beam area affected by the turbulence. Note also, that this definition leads to an r_o larger than that for a plane wave for constant C_n^2.

$$r_o = \left[\frac{2.905}{6.88}\left(\frac{2\pi}{\lambda}\right)^2 \int_{path}^{R} C_n^2(h(z))\left(\frac{R-z}{R}\right)^{5/3} dz\right]^{-3/5}$$

$$r_o = \left[0.422k^2 \int_{path}^{R} C_n^2(h(z))\left(\frac{R-z}{R}\right)^{5/3} dz\right]^{-3/5}$$

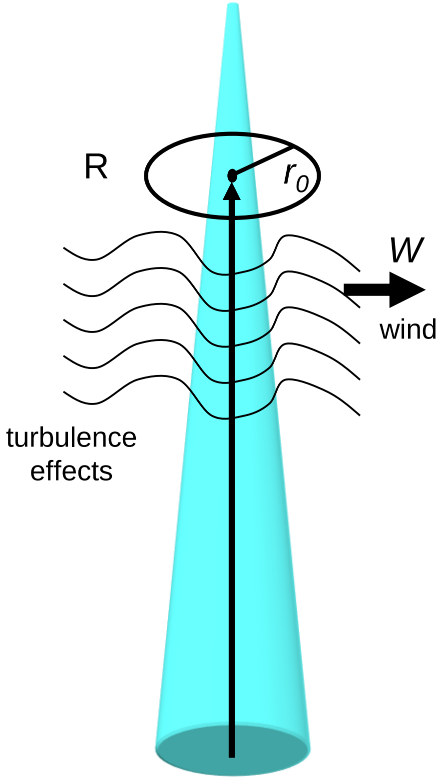
r_o = 1 – 10 cm (tactical), 0.1 – 1 m (strategic)

Recall wave number,

$$k = \left(\frac{2\pi}{\lambda}\right)$$

For constant C_n^2

$$r_o = 3.02\left(C_n^2 R k^2\right)^{-3/5}$$



The Atmosphere

The University of New Mexico

Atmospheric Effects

- r_0 : Fried Parameter is the diameter in the telescope aperture over which the atmospheric turbulence induce phase aberration is nearly linear
- For aperture diameter D > r_0 there is little improvement in the Strehl ratio of long exposure imaging or targeting.
- If the structure constant C_n^2 is constant:

$$r_0 = 0.185 \frac{\lambda^{6/5}}{R^{3/5} (C_n^2)^{3/5}}$$

$$r_0 = 0.33 \frac{\lambda^{6/5}}{R^{3/5} (C_n^2)^{3/5}}$$

Plane Wave Spherical Wave

Assuming 1 micron wavelength and constant weak turbulence ($C_n^2 = 1\text{x}10^{-17}$)

r_0 Plane Wave	r_0 Spherical Wave	Range
74 cm	131 cm	10 km
19 cm	33 cm	100 km
5 cm	8 cm	1000 km

The Atmosphere

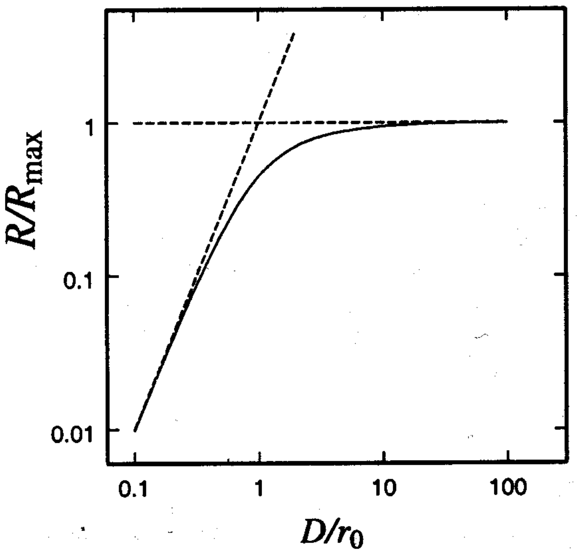
Atmospheric Effects

Fried originally developed r_0 from an imaging perspective:

> This is the radius above which imaging resolution does not improve with increasing telescope size. However, larger telescopes still collect more light, even if resolution does not increase.

While not a sharp cut-off, we see that according to the metric Fried used (area under OTF curve), this is the 'knee' in the curve.

For a laser weapon, this metric is closely related to the performance metric of Strehl ratio. Thus apertures larger than r_0, without AO, will suffer performance decreases.



The Atmosphere

Atmospheric Effects

Recall, the diffraction limited angle :

$$\theta_{diff} \sim \lambda / D$$

If we had a D = 1 m beam director for a λ = 1 μm source, diffraction would produce a 1 μrad divergence.

“Seeing” is the atmospherically limited angular resolution:

$$\theta_{seeing} \sim \lambda / r_o$$

On a mountaintop with good conditions, θ_{seeing} ~ 0.5 arcsec (5 μrad).

For the example above, if the Fried coherence length were $r_o < 1$ m, then seeing would be significantly affected.

Note: “Seeing” for imaging applications shares a similar interpretation to spot size for HEL propagation.

The Atmosphere

Atmospheric Effects

Isoplanatic Angle (radians), θ_o

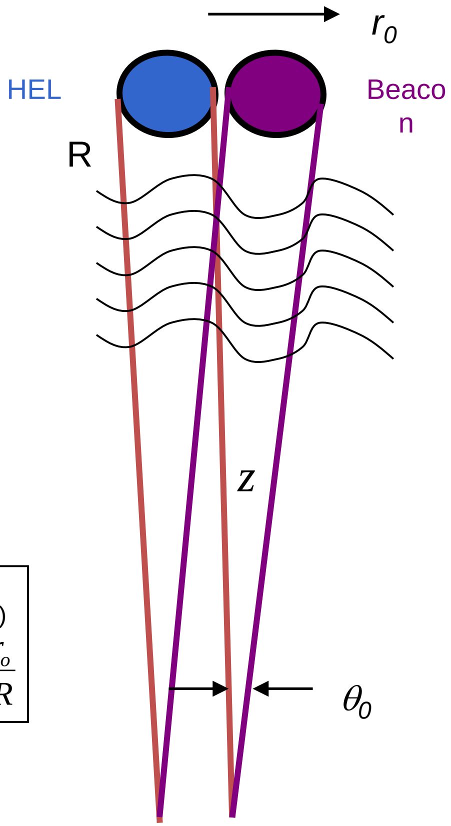
Measure of angular coherence of atmosphere along path of interest. Represents the integrated effect of refractive-index fluctuations along a path weighted by altitude. Small values indicate strong turbulence. θ_o is the angle over which the effect of turbulence on the wave front is small (RMS difference between paths of 1 radian). If beacon and kill beams do not fall within this angle, performance degrades.

$$\theta_o = \left[2.905 k^2 \int_{path} C_n^2(z) z^{5/3} dz \right]^{-3/5}$$

For $C_n^2 \neq f(z)$

$$\theta_o = 0.314 \frac{r_o}{R}$$

If θ_o < (λ / D), then AO less useful



The Atmosphere

Atmospheric Effects

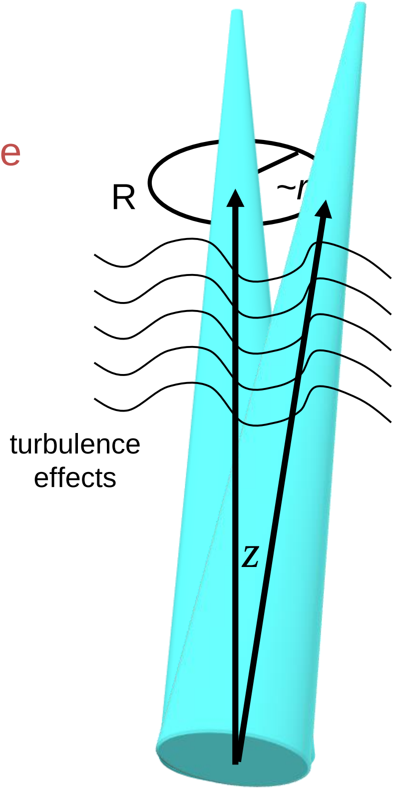
Isoplanatic Angle (radians), θ_o, for a spherical wave

$$\theta_o = \left[2.905k^2 \int_{\text{path}} C_n^2(z) z^2 (1 - z/R)^{-1/3} dz \right]^{-3/5}$$

For constant C_n^2

$$\boxed{\theta_o = 0.398 \frac{r_o}{R^{6/5}}}$$

If $\theta_o < (\lambda / D)$, then AO is less effective

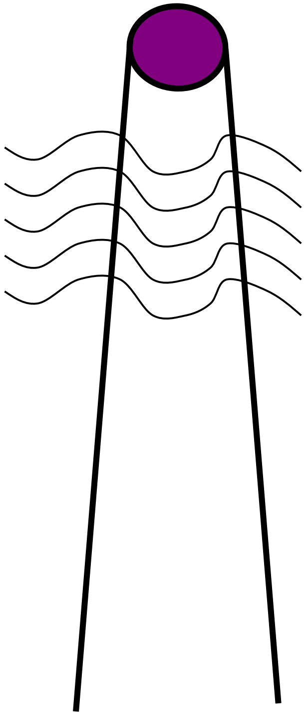


Electromagnetic Wave Propagation in Turbulence, Evaluation and Application of Mellin Transforms, Second Edition, Richard J. Sasiela

The Atmosphere

Atmospheric Effects

Effect of turbulence location depends on parameter of interest.



For beam focused on target:

r_0 is weighted near the receiver (telescope)

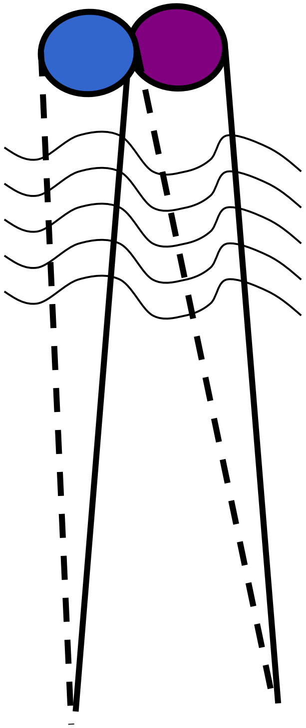
$$r_o = \left[0.422k^2 \int_{path}^{R} C_n^2(h(z))\left(\frac{R-z}{R}\right)dz\right]^{-3/5}$$

θ_0 is weighted near the target

$$\theta_o = \left[2.905k^2 \int_{path} C_n^2(z)z^2(1-z/R)^{-1/3}\,dz\right]^{-3/5}$$

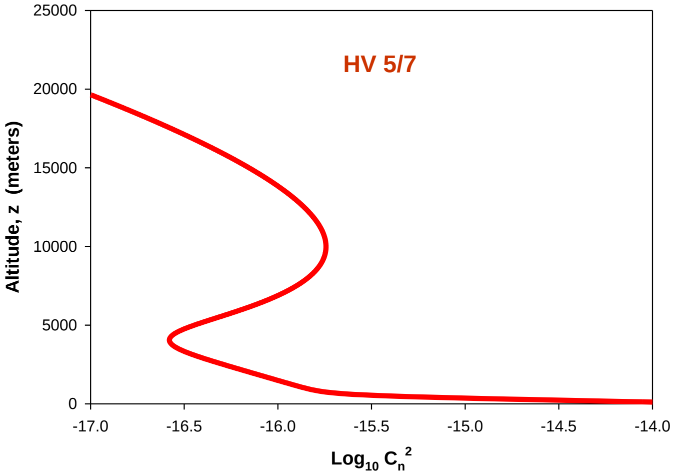
σ_χ^2 is weighted toward the center

$$\sigma_\chi^2 = 0.563k^{7/6}\int_0^R C_n^2 z^{5/6}\left(\frac{R-z}{R}\right)^{5/6} dz$$



The Atmosphere

Atmospheric Effects



$$C_n^2(h) = 5.94\times10^{-53}\left(\frac{v}{27}\right)^2 h^{10}e^{-h/1000} + 2.7\times10^{-16}e^{-h/1500} + Ae^{-h/100}$$

Using the Hufnagle Valley C_n^2 profile with:

v= 21 m/s

A=1.7 x 10^{-14} $m^{-2/3}$

yields:

r_o = 5 cm

θ_o = 7 μrad

and is called HV 5/7.

The Atmosphere

Atmospheric Effects

How to calculate C_n^2, C_T^2, C_v^2

$$\boxed{C_T^2 = a^2\left(\frac{K_H}{K_M}\right)L_o^{\frac{4}{3}}\left(\frac{\partial\theta}{\partial Z}\right)^2}$$

$$\frac{\partial\theta}{\partial z} = \left(\frac{\partial T}{\partial z} + \gamma_d\right)^2$$

$$a^2 = 2.8$$

L_o = mixing length
Effectively an outer scale;
Estimated at ~100 to 200 m

$$\mathrm{Ri} = \left(g\frac{\partial \ln\theta}{\partial z}\right)\Big/\left(\frac{\partial V}{\partial z}\right)^2$$

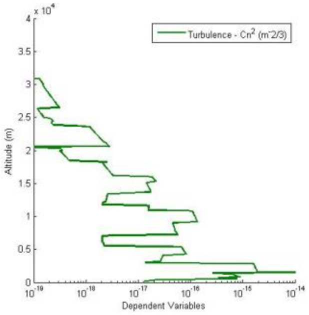
$$C_n^2 = \left(79\ x\ 10^{-6}\frac{P}{T^2}\right) C_T^2$$

$$\frac{K_H}{K_M} = \left\{\frac{\frac{1}{7Ri,} for Ri \geq 1,}{\frac{1}{6.873Ri + \frac{1}{1+6.873Ri}} for 0.01 < Ri \leq 1.}\right.$$

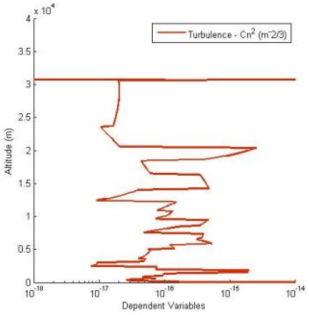
$$\boxed{C_n{}^2 = 2.8\frac{K_H}{K_M}\left(\frac{(79\ x\ 10^{-6}P)}{T^2}\right)^2 L_o{}^{4/3}\left(\frac{\partial T}{\partial Z} + \gamma_d\right)^2}$$

$$\boxed{C_v^2(z) = (0.714)C_n^2(z)\left(\partial\frac{\langle \mathbf{v}(z)\rangle}{\partial z}\right)^2\left(\nabla\langle n\rangle\right)^{-2}}$$

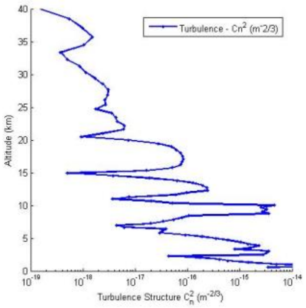
$$C_n^2(z) = \frac{a}{2}\left[\Delta\langle n\rangle\Big/\frac{\partial\langle v(z)\rangle}{\partial z}\right]^2 C_v^2$$



Climo-derived



NWP-derived



AIRS-derived

R. J. Alliss and B. D. Felton, "Validation of Optical Turbulence Simulations from a Numerical Weather Prediction Model in Support of Adaptive Optics Design", Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, Wailea, Maui, Hawaii, September 1-4, 2009, Ed.: S. Ryan, The Maui Economic Development Board., p.E54.

D. E. Fung, "Relationship between the refractive-index and velocity structure constant AR-45", Science Applications International Corporation technical report, 28 July 2003.

J. O. Kondo, O. Kanechika, and N. Yasuda, "*Heat and momentum transfers under strong stability in the atmospheric surface layer,*" Journal Atmos. Sci., 35, 1012–1021; 1978.

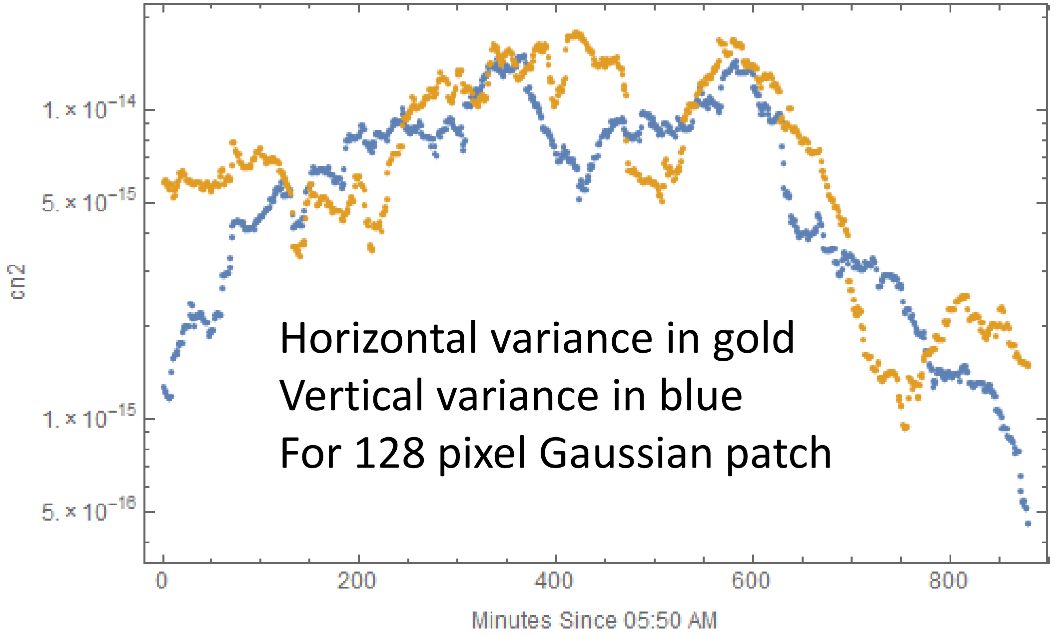
V. Tatarskii, "The effects of the turbulent atmosphere on wave propagation," translation, Published for NOAA by the Department of Commerce and the National Science Foundation, Washington D.C. (1971). Israel Program for Scientific Translations.

The Atmosphere

Atmospheric Effects

Measuring C_n^2 - Time Lapse Imaging

By presuming Kolmogorov statistics and constant turbulence along the path, we can estimate its value:



Horizontal variance in gold
Vertical variance in blue
For 128 pixel Gaussian patch

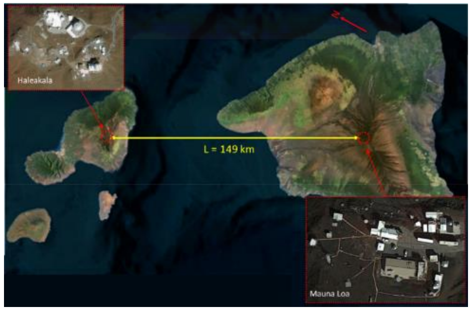
256 x 256 pixels. 10 minutes between images.
Clearest day we took pictures.

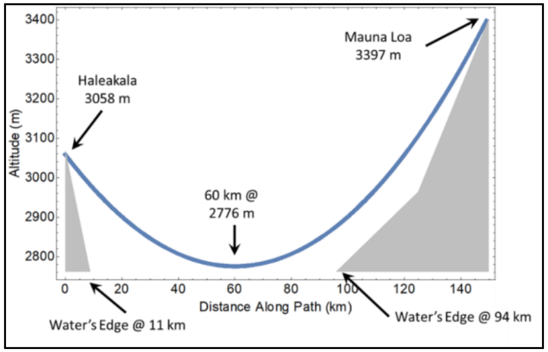
The Atmosphere

Atmospheric Effects

Extended-Range Comprehensive Atmospheric Optics Sensing (ERCAOS)

Using LED beacons on Mauna Loa, and cameras on Haleakala, we estimated the turbulence in the middle of the 149 km path.

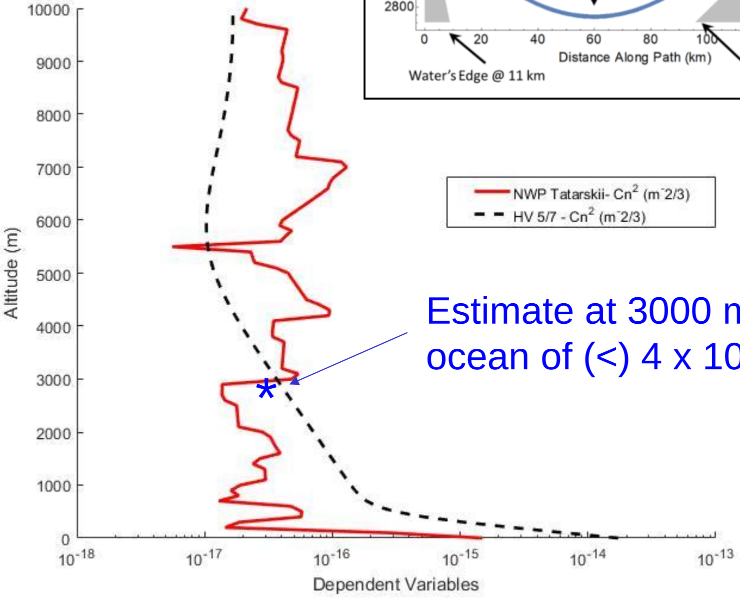




The result of this is just a single number (per time interval):
Subject to further revision, we achieve a path integrated turbulence at 3000 m over the ocean of (<) 4 x 10^{-17} $m^{-2/3}$

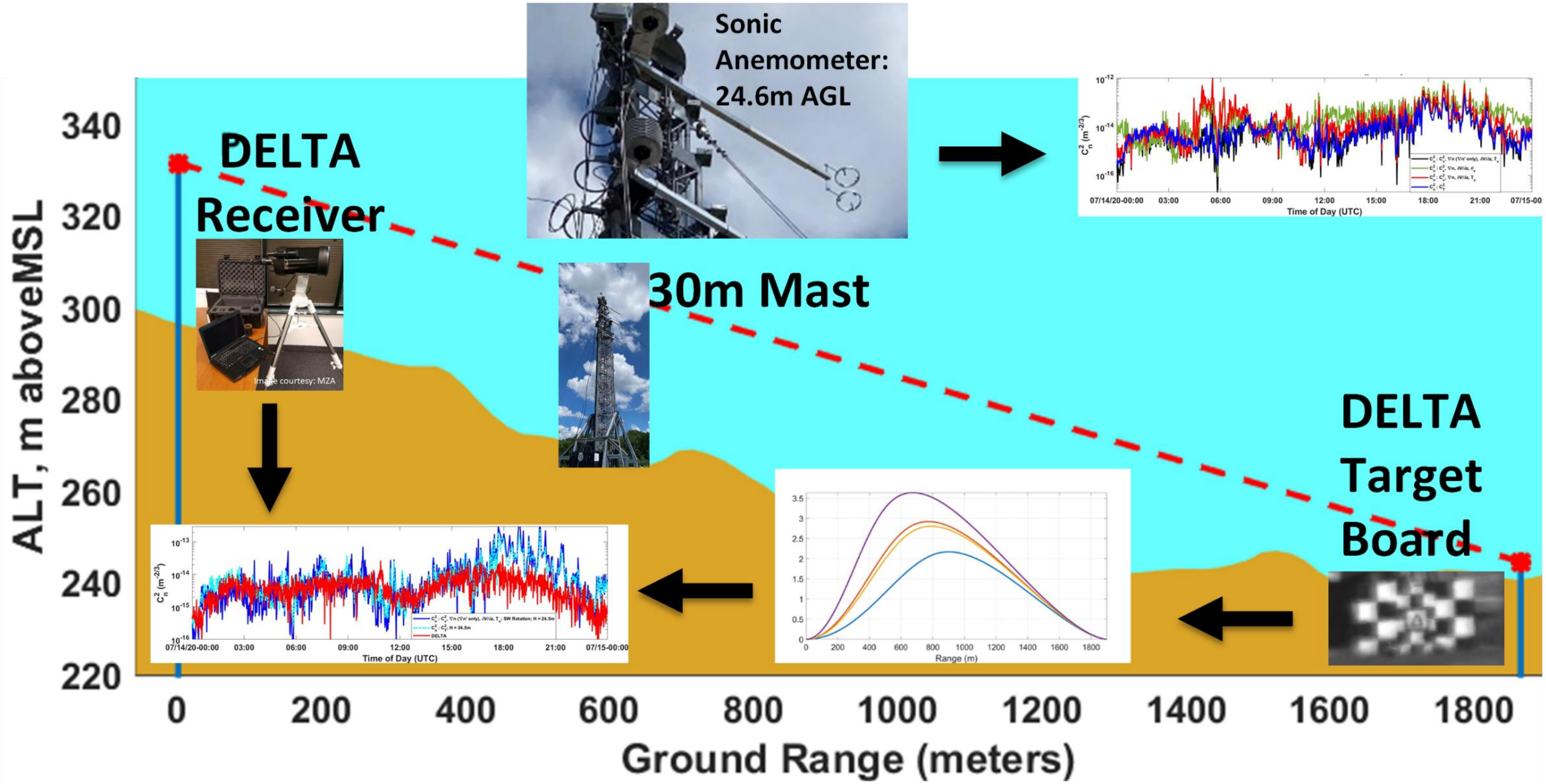
I say less than because including small singular values in the pseudo-inversion leads to a negative C_n^2 in this case, setting a higher tolerance leads to the value given above. The data here at least suggests the turbulence is no higher than this.

This is in agreement with HV5/7 and other turbulence models as well as …



Estimate at 3000 m over the ocean of (<) 4 x 10^{-17} $m^{-2/3}$

Sonic Anemometers and DELTA Turbulence Sensors

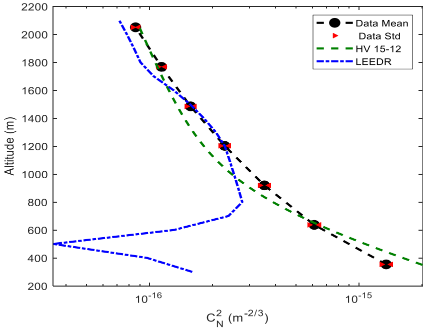


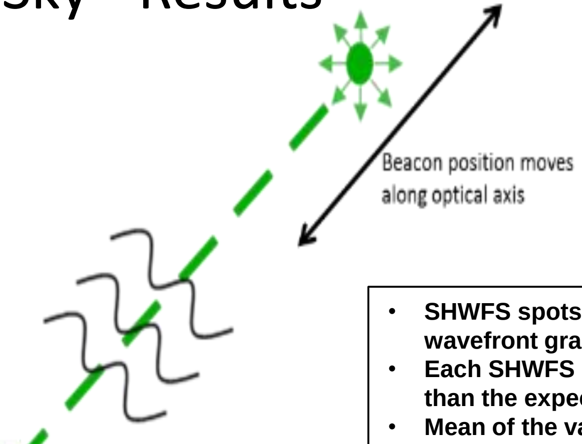
Fiorino, S., S. Bose-Pillai, and K. Keefer, 2021: "Re-Visiting Acoustic Sounding to Advance the Measurement of Optical Turbulence" *Applied Sciences* **11**(16):7658. doi.org/10.3390/app11167658.

TARDIS Data Collections: On Sky - Results

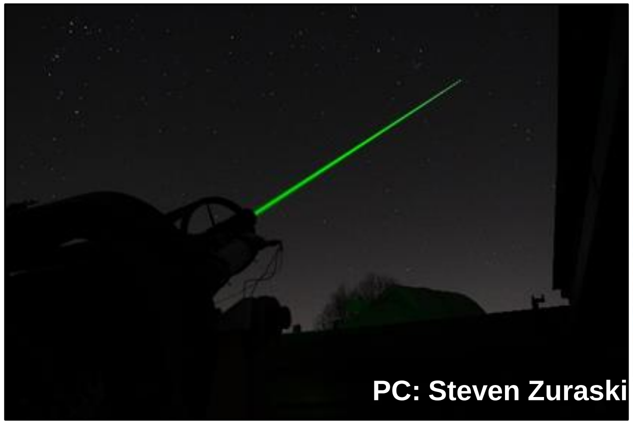
Main System Qualities

- 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

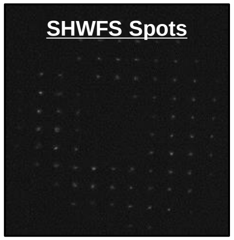


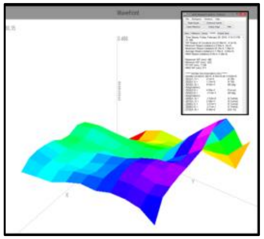


- **SHWFS spots representing zonal wavefront gradients**
- **Each SHWFS sub-aperture is smaller than the expected r_0**
- **Mean of the variance of the spot tilts is used to calculate r_0**
- ***Based on r_0* differencing within a “frozen” atm. window segmented C_n^2 can be calculated**



PC: Steven Zuraski





$$r_0 = \frac{0.299D}{\langle\sigma^2\rangle^{3/5}}$$

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

The Atmosphere

Atmospheric Effects

Greenwood Frequency: A measure of how fast the control system must respond to correct for turbulent atmosphere. Represents the integrated effect of refractive index fluctuations with wind speed factored in. Large values typically indicate strong turbulence.

$$f_G = \left[0.102 k^2 \int_{Path} C_n^2(z) W_E^{5/3}(z) dz \right]^{3/5}$$

$f_G < 100$ Hz (slow close target); $f_G \sim 1000$ Hz (fast distant target)

For constant wind along the entire path,

$$f_G = 0.421 \frac{W_E}{r_o} \quad W_E = effective\ wind\ speed$$

The Atmosphere

Atmospheric Effects

- Anisoplanatism, literally, “not in the same plane.”
  - Beacon and object may not share identical effects from turbulence.
  - Light from the beacon may not pass through the same atmospheric turbulence as the light going to the target that must be corrected.

- Types of anisoplanatism (with relevant parameter) and cause
  - Spatial anisoplanatism (Fried parameter r_0): spatial extent of beacon and target beams.
    - r_0 is radius of circle where phase aberrations are still “small”
  - Angular anisoplanatism (anisoplanatic angle θ_0): angular separation of beacon and target beams.
    - θ_0 is max angle between beams while phase difference between the two is still “small”
  - Temporal anisoplanatism (Greenwood and Tyler frequency $f_{G,}$ $f_{T,}$) temporal separation of beacon and target beams.
    - f_G is max time delay between two beams going through same path while phase difference between the two is still “small”
  - Focus anisoplanatism: difference in measured turbulence due to beacon not located at target
  - Beacon anisoplanatism: the beacon extends over more than one isoplanatic patch
  - Chromatic anisoplanatism: difference in wavelength between beacon and target beams alters propagation due to dispersion.

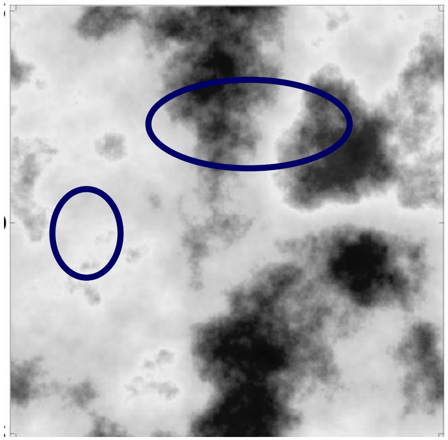
- Bottomline: the quality of the compensated beam can still be degraded due to differences between turbulence experienced by the beacon and the actual turbulence experienced by the primary beam.

The Atmosphere

Atmospheric Effects

- Scintillation is the effect we see when stars “twinkle.”
- Scintillation is the intensity variation due to the phase distortions propagating through space from the source to the observer.
- Scintillation is subject to aperture averaging.
  - Since our eye is small, large fluctuations occur in received irradiance.
  - Larger apertures diminish this effect by averaging over the aperture.
- Conventional AO systems do not correct for scintillation effects.

The smaller aperture will see large fluctuations in average intensity as the field moves across the aperture; whereas the average intensity across the larger aperture is relatively constant.



The scintillation index σ_I^2 is defined as

$$\sigma_I^2 \equiv \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1$$

The Atmosphere

Atmospheric Effects

Rytov Variance: Turbulence induced scintillation effects result from amplitude fluctuations. Rytov theory fails to predict scintillation saturation. Scintillation Strehl is often based on the Rytov number:

Plane Wave

$$\sigma_\chi^2 = 0.563k^{7/6}\int_0^R C_n^2 z^{5/6}\,dz$$

For constant C_n^2

$$\sigma_\chi^2 = 0.307k^{7/6}R^{11/6}C_n^2$$

Spherical Wave

$$\sigma_\chi^2 = 0.563k^{7/6}\int_0^R C_n^2 z^{5/6}\left(\frac{R-z}{R}\right)^{5/6} dz$$

$$\sigma_\chi^2 = 0.124k^{7/6}R^{11/6}C_n^2$$

Tyler Frequency: characteristic frequency of the turbulence induced tilt.

$$f_T = 0.368D^{-1/6}\lambda^{-1}\sqrt{\int_0^R C_n^2\left[h(z)\right]\left|V(z)\right|^2 dz}$$

For constant wind and C_n^2

$$f_T = 0.368D^{-1/6}\lambda^{-1}v_{eff}\sqrt{C_n^2 R}$$

The Atmosphere

Atmospheric Effects

Estimates on turbulence parameters

- Assume uniform C_n^2 along the path length
- Strong turbulence near the earth's surface
- Weak turbulence high in the atmosphere

C_n^2 ($m^{-2/3}$)	Range R (km)	Fried r_0 (m)	Isoplanatic θ_0 (rad)	Greenwood f_G (Hz)
Weak 10^{-17}	1000	4.6×10^{-2}	2.6×10^{-8}	275
	100	0.19	1.1×10^{-6}	69
	10	0.74	4.2×10^{-5}	17
Strong 10^{-13}	1000	1.9×10^{-4}	1.1×10^{-10}	6.9×10^{4}
	100	7.4×10^{-4}	4.2×10^{-9}	1.7×10^{4}
	10	2.9×10^{-3}	1.7×10^{-7}	4.4×10^{3}

Beam width due only to turbulence

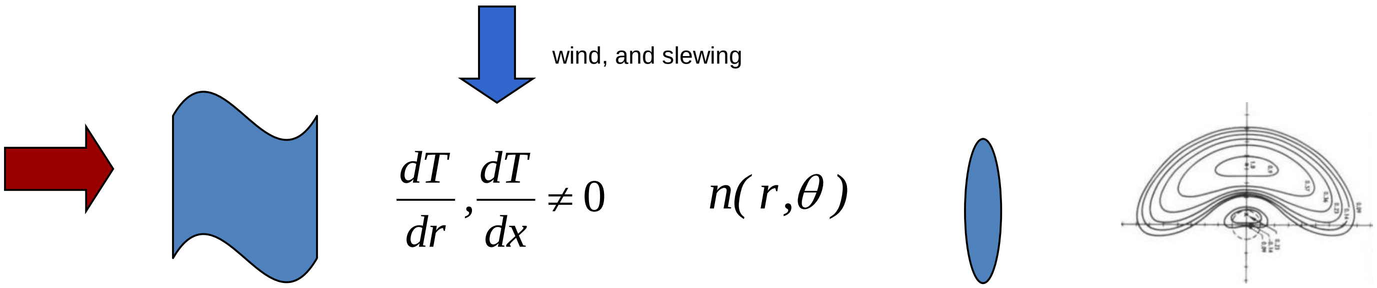
$$a_t = \frac{\sqrt{2}\lambda R}{\pi\, r_0}$$

Weak turbulence at 100 km, $a_t = 0.24$m

The Atmosphere

Atmospheric Effects

Thermal Blooming: The effect that characterizes an intense laser beam that is passed through an absorbing medium, causing the absorbed energy to produce density changes that can alter the intensity distribution of the beam and shift it away from the intended direction of propagation. Thermal blooming is an effect associated with heating the atmosphere.



wind, and slewing

$$\frac{dT}{dr}, \frac{dT}{dx} \neq 0$$

$$n(r,\theta)$$

Laser beam

Absorbing atmosphere

Heating, Temperature Gradients

Variations in index of refraction

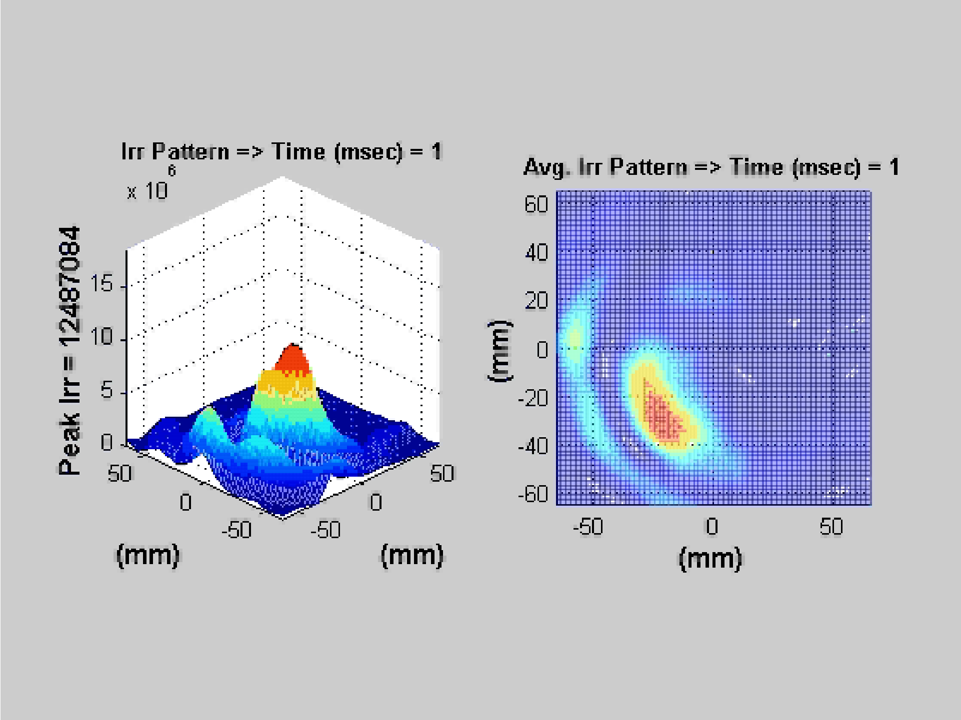
Focusing effects

Modified irradiance pattern

The Atmosphere

Atmospheric Effects

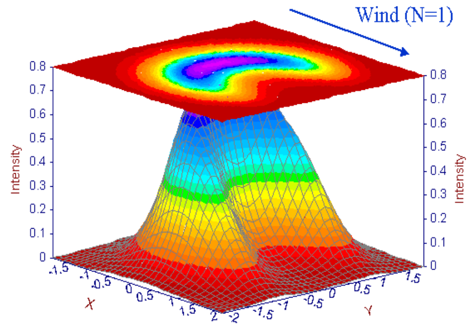
Laser beams are often highly aberrated and exhibit a total Strehl, S < 1.



These irradiances patterns were computed using the wave optics simulation ACS for a 50 kW laser in an air-to-ground engagement with a 9 km range for atmospheric conditions with significant thermal blooming.

The time-average irradiance pattern represents the accumulation of fluence on the target and illustrates the classical crescent shape associate with thermal blooming.

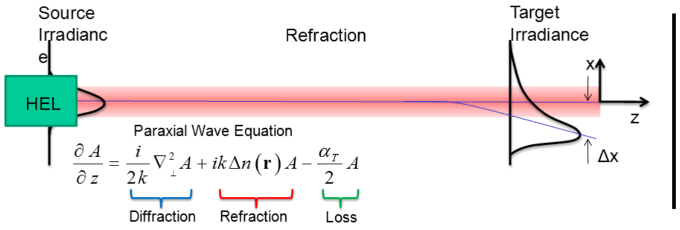
Thermal blooming produces an intensity pattern with a crescent shape, turned into the wind direction.



The Atmosphere

Atmospheric Effects

N_d provides measure of steady state, "whole-beam" thermal blooming accounting for flat-top beam *diffraction, focus, and proportional clearing wind*



Thermal Blooming due to smoke

Thermal Blooming Distortion Number, N_D

$$N_D = -\frac{4\sqrt{2}kP}{\rho_0 C_p}\int_{path}\frac{\alpha(z)T(z)n_T(z)}{V_{wind}(z)D(z)}dz$$

$\alpha(z)$= absorption coefficient

V_{wind} = effective wind speed

P = laser power

z = propagation distance

k = $2\pi/\lambda$

D(z) = beam diameter

D = primary aperture diameter

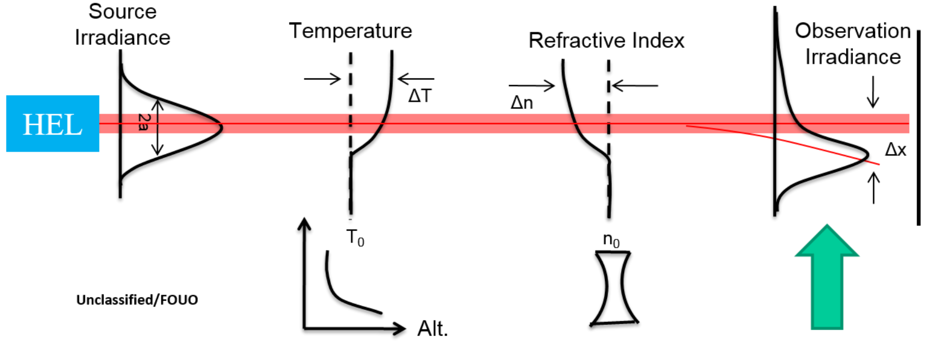
ρ_o = 1.2 kg m^{-3}

C_p = 1005 J kg^{-1} K^{-1}

T(z) = transmission at range z

n_T (z) = thermal refractive gradient

R = total slant range



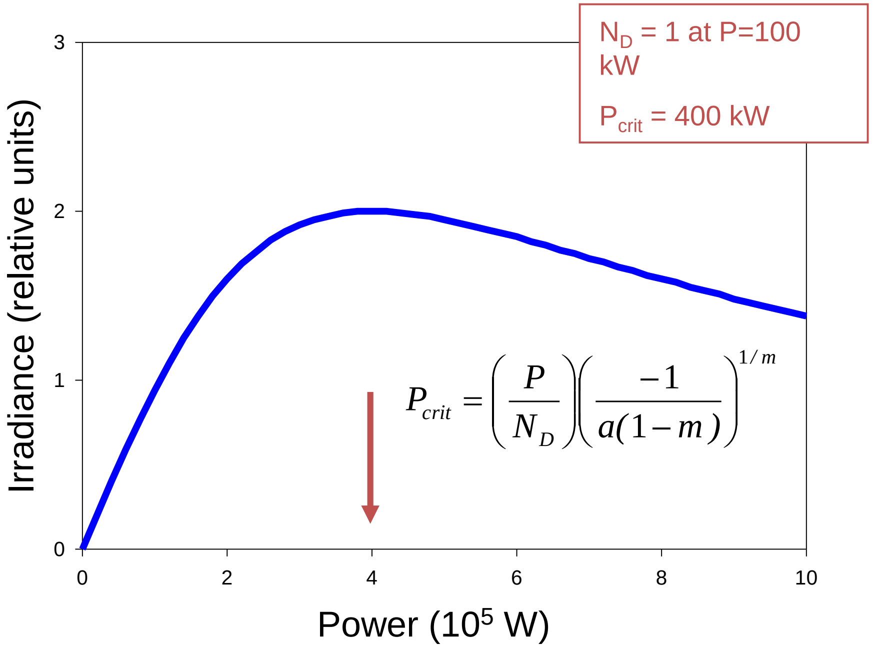
Unclassified/FOUO

Thermal Blooming is a significant problem when $N_D > 25$

The Atmosphere

Atmospheric Effects

The critical power for thermal blooming defines the maximum deliverable irradiance



N_D = 1 at P=100 kW

P_{crit} = 400 kW

$$P_{crit} = \left(\frac{P}{N_D}\right)\left(\frac{-1}{a(1-m)}\right)^{1/m}$$

Thermal Blooming is negligible for:

- high altitudes (low absorption), including ABL
- minimal atmosphere, including SBL
- laser wavelengths with very little absorption

Thermal Blooming important for:

- low altitude (high absorption), including THEL
- slow moving targets, including ATL

ABL = Airborne Laser

THEL = Tactical High Energy Laser

SBL = Space Based Laser

ATL = Advanced Tactical Laser

The Atmosphere

Atmospheric Effects

Element	Parameter	Value	Scale / Effect
Primary Aperture	Diameter D	$D = 0.1 - 10$ meters	λ/D Diffraction
Fast Steering Mirror	Jitter ϕ, j	$\phi = 10 - 200$ nradian	$j / (\lambda/D)=0.2\text{-}1.0$ Blurred Beam
Deformable Mirror	Number of actuators, N	$N = 10^1 - 10^3$	High order AO correction
Wavefront Sensor	Sub-aperture size, d	$d / r_o \sim 1$ (r_o = Fried Coherence Length)	$N \sim (D/d)^2$ Fitting Error
Beacon / Illuminator	Beam radius at target, a	$(a/R) / \theta_o < 1$ (θ_o = Isoplanatic Angle, R =Range)	Sense Turbulence Track Target
Control System	AO Bandwidth, f	$(f / f_G) > 2$ (f_G = Greenwood Frequency)	Temporal fluctuations

The Atmosphere

Atmospheric Effects

4D Weather Cubes Studies

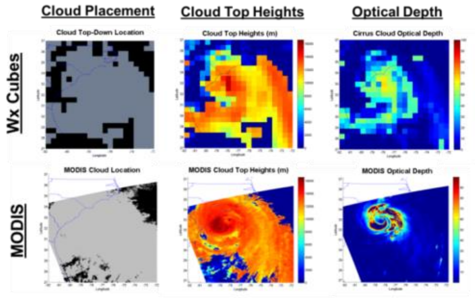
Weather Cubes are analytical, visualization, and decision aid tools which accurately convey multi-spectral (UV through RF) propagation and atmospheric effects.

Cloud & Rain fields are generated using the following NWP outputs for realistic sky conditions:

- **Relative Humidity**
- **Vertical Velocity**
- **Precipitation Totals**

- **Anchor: V&V'd Laser Environmental Effects Definition and Reference (LEEDR) tool**
  - **Incorporates probabilistic climatology and NOAA global-gridded Numerical Weather Prediction (NWP) data – based on global observations – for forensic, nowcast and forecast analyses**
- **Blends first principles atmospheric processes and constituent (e.g. droplets, aerosols) microphysical / optical properties to characterize optical turbulence, clouds, rain, and aerosol radiative effects**

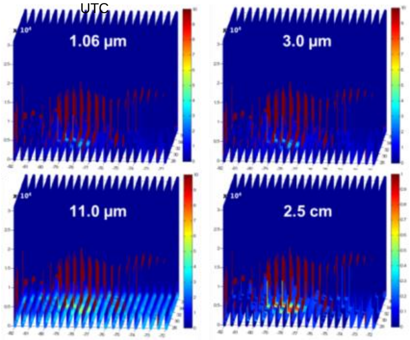
Cloud Field Verification



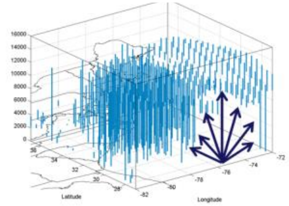
Mission Planning & System Analysis Implications

- **Using HPCs, generate climatologies with 10+ years of NWP**
- **Laser/BILL/TILL performance analysis studies**
- **CFLOS tables for data-void regions using NWP-generated Cloud Fields**

Hurricane Arthur – 03 July 2014 1800 UTC

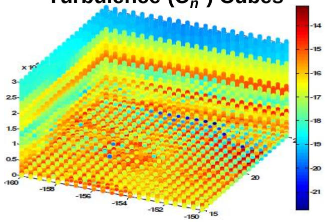


3D Cloud Locations

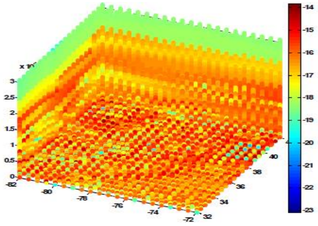


CFLOS determined for various look angles

Turbulence (C_n^2) Cubes



Hawaii Region at 0800L

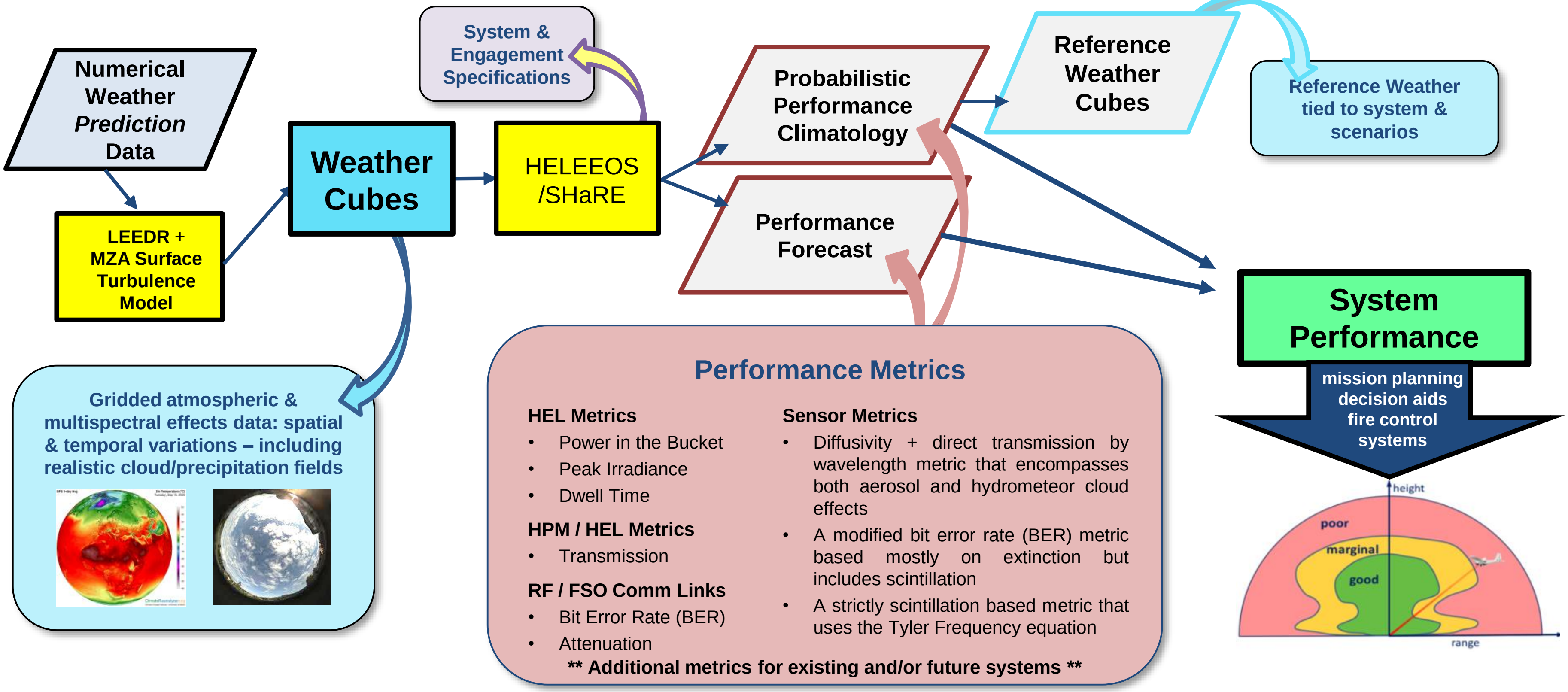


Carolina Coastal Region at 1400L

18 August 2016 at 1800 UTC

4D Weather Cube

Flow Chart of System Performance Assessments using Weather Cubes



Numerical Weather *Prediction* Data

LEEDR + MZA Surface Turbulence Model

Weather Cubes

System & Engagement Specifications

HELEEOS /SHaRE

Probabilistic Performance Climatology

Performance Forecast

Reference Weather Cubes

Reference Weather tied to system & scenarios

System Performance

mission planning
decision aids
fire control systems

Gridded atmospheric & multispectral effects data: spatial & temporal variations – including realistic cloud/precipitation fields

Performance Metrics

HEL Metrics

- Power in the Bucket
- Peak Irradiance
- Dwell Time

HPM / HEL Metrics

- Transmission

RF / FSO Comm Links

- Bit Error Rate (BER)
- Attenuation

Sensor Metrics

- Diffusivity + direct transmission by wavelength metric that encompasses both aerosol and hydrometeor cloud effects
- A modified bit error rate (BER) metric based mostly on extinction but includes scintillation
- A strictly scintillation based metric that uses the Tyler Frequency equation

**** Additional metrics for existing and/or future systems ****

Probabilistic Performance Binning

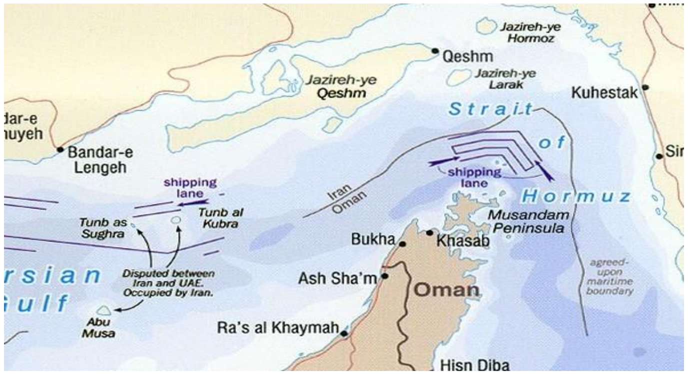
Southern Persian Gulf (SPG)

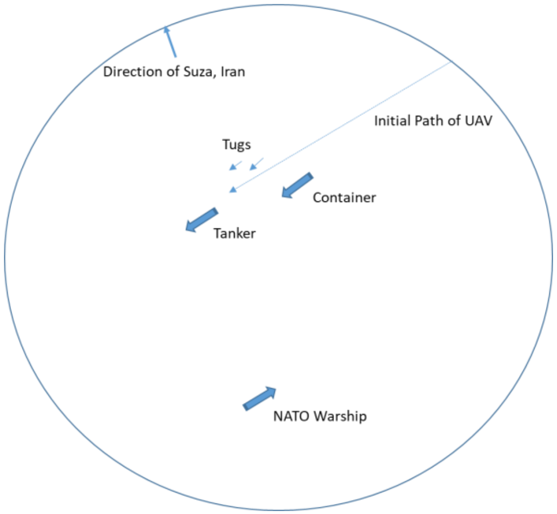
Analysis Period: 2007-2017

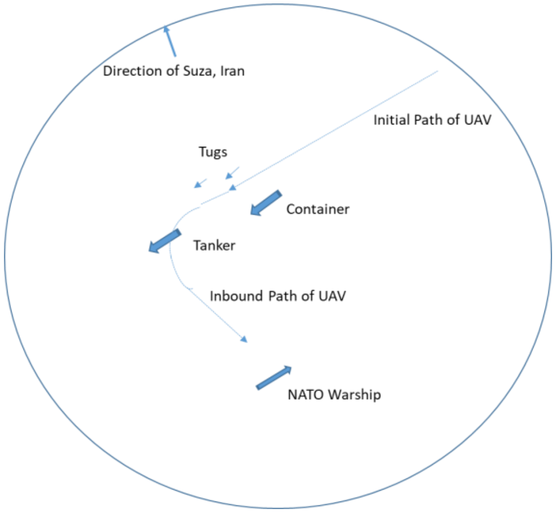
Performance Binning Specifications

System & Engagement Parameters

Location	HEL Designation	λ (μm)	Ap Diam (m)	Power (kW)	BQ	Platform Jitter (rad)	Platform Alt (m)	Platform Speed (m/s)	Platform Hdg (deg)	Platform Az (deg)	Target Alt (m)	Range (km)	Target Speed (m/s)	Target Hdg (deg)
Gulf	CUAS1	1.06	0.4	50	2	3.E-06	15	10	75	70	200	5	40	250
Gulf	CUAS2	1.06	0.4	100	2	3.E-06	15	10	75	70	200	5	40	250
Gulf	CUAS3	1.06	0.4	150	2	3.E-06	15	10	75	70	200	5	40	250

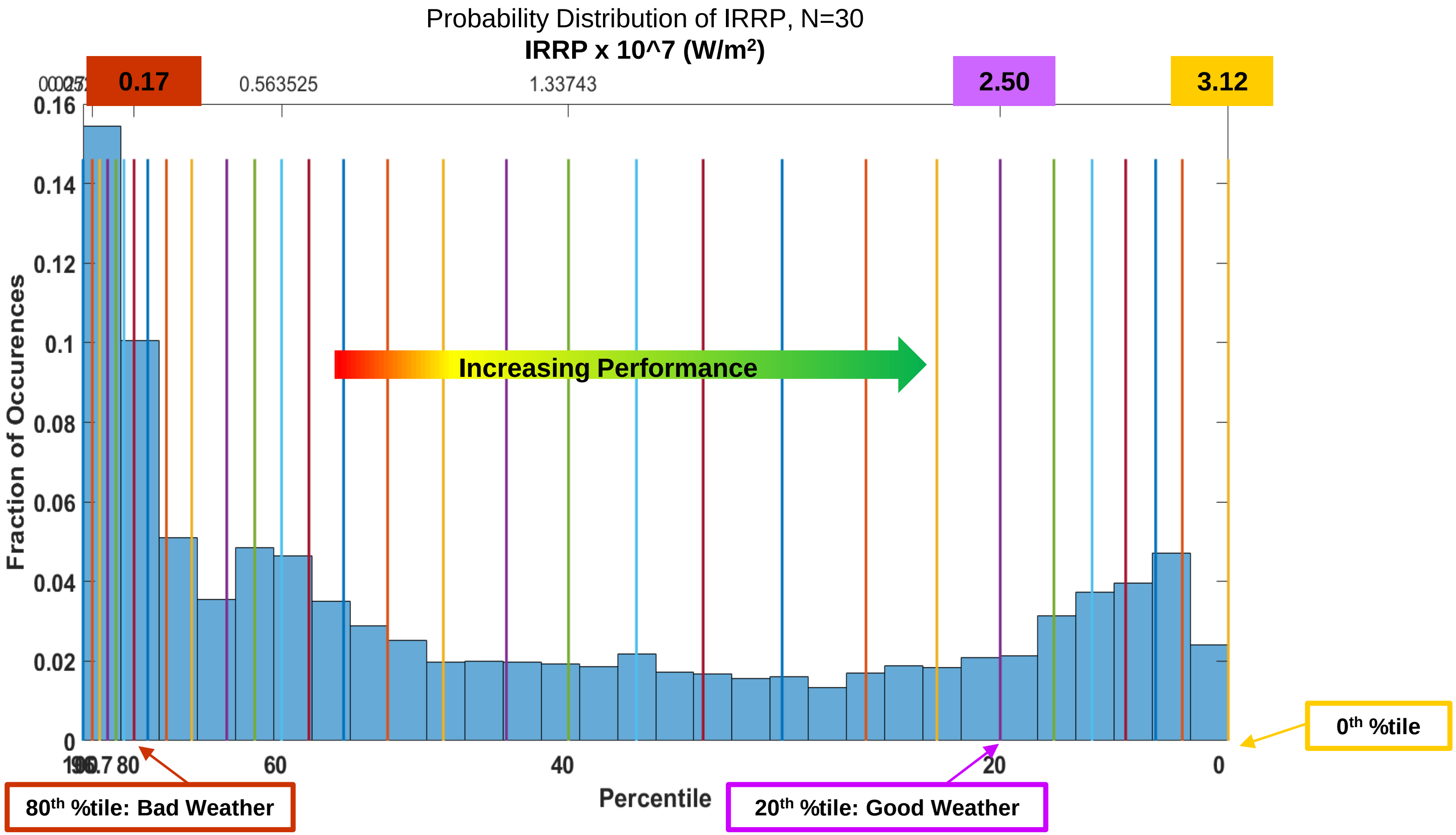






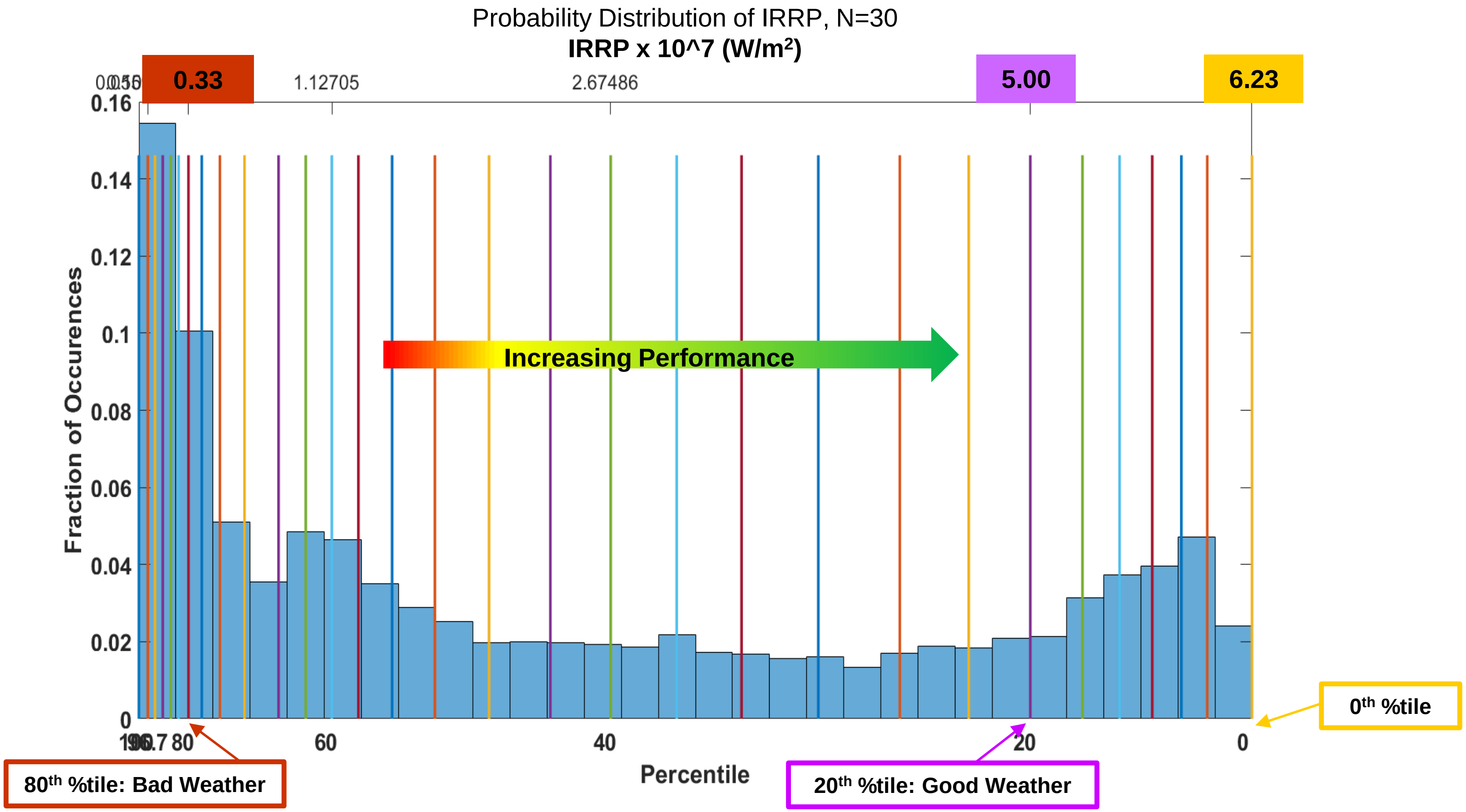
SPG Binning

CUAS1



SPG Performance Binning

CUAS2



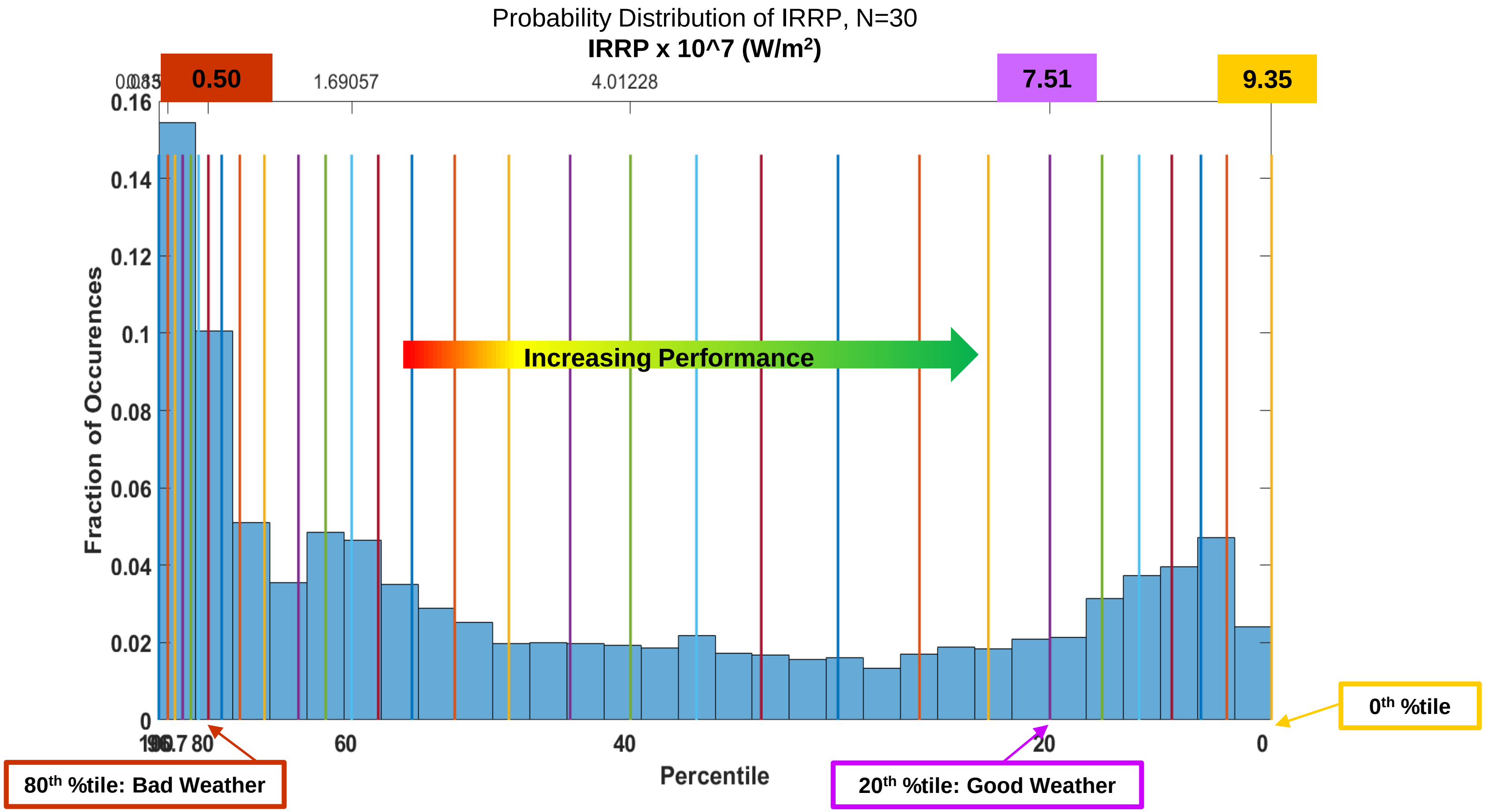
80th %tile: Bad Weather

20th %tile: Good Weather

0th %tile

SPG Performance Binning

CUAS3



80th %tile: Bad Weather

20th %tile: Good Weather

0th %tile

Probabilistic Performance Binning

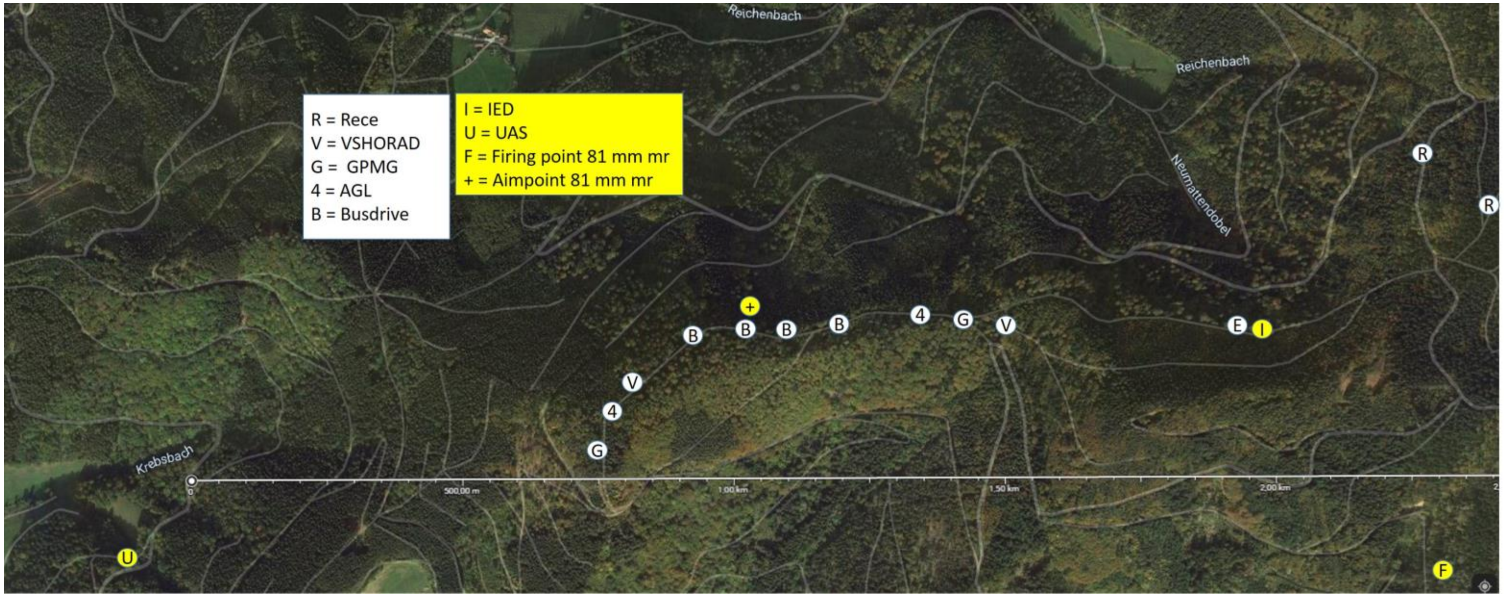
Black Forest, Germany

Analysis Period: 2007-2017

Performance Binning Specifications

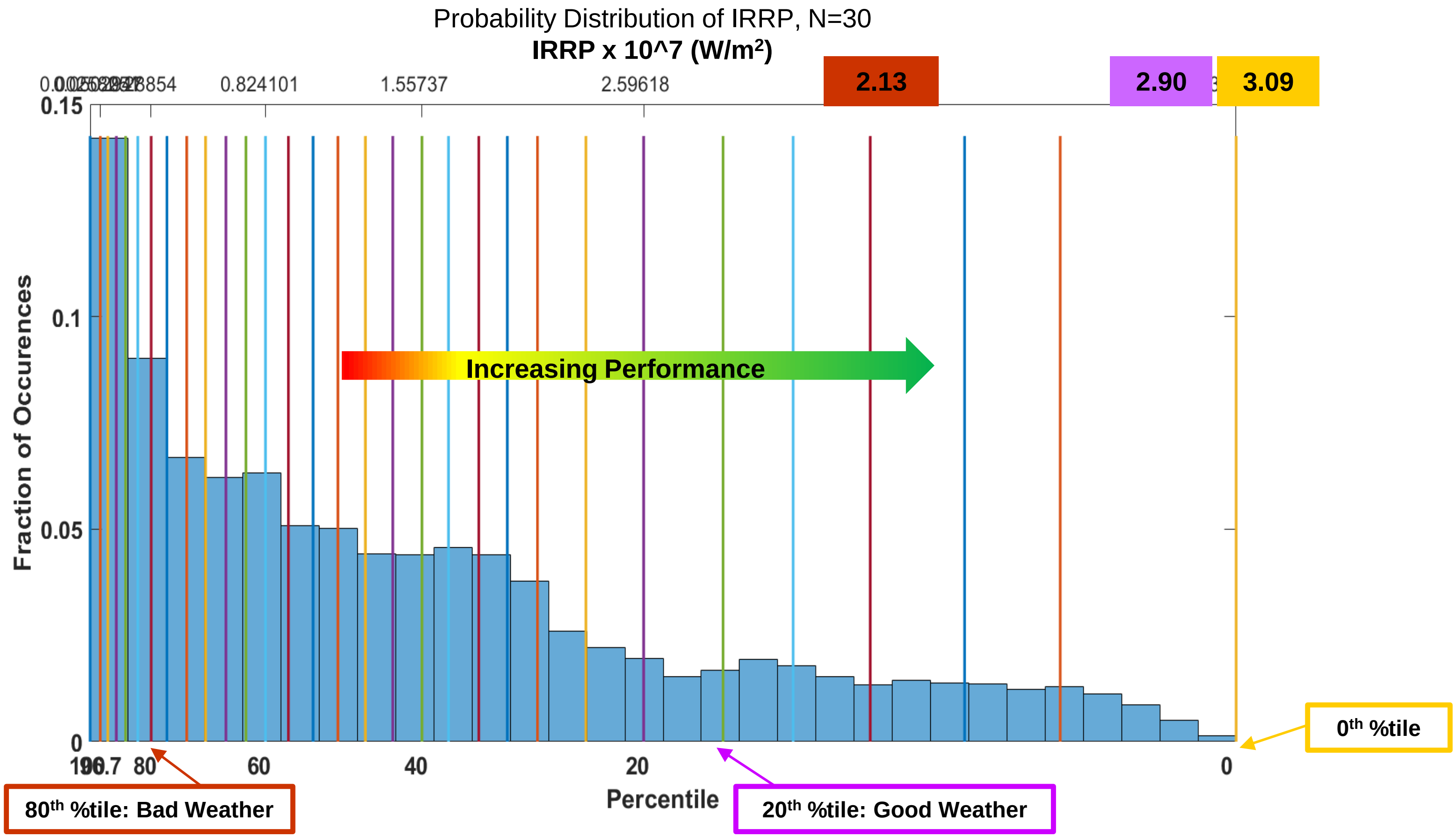
System & Engagement Parameters

Location	HEL Designation	λ (µm)	Ap Diam (m)	Power (kW)	BQ	Platform Jitter (rad)	Platform Alt (m)	Platform Speed (m/s)	Platform Hdg (deg)	Platform Az (deg)	Target Alt (m)	Range (km)	Target Speed (m/s)	Target Hdg (deg)
	IED	1.07	0.15	3/5/10	1.5	2.E-06	3	0	0	0	0	0.1	0	0
Platoon/Patrol	CUAS	1.07	0.3	10/30/50	1.5	2.E-06	3	0	0	240	50	1.7	10	50
Black Forest	CRAM	1.07	0.3	10/30/50	1.5	2.E-06	3	0	0	120	900	1.7	100	300



Black Forest Performance Binning

CUAS1



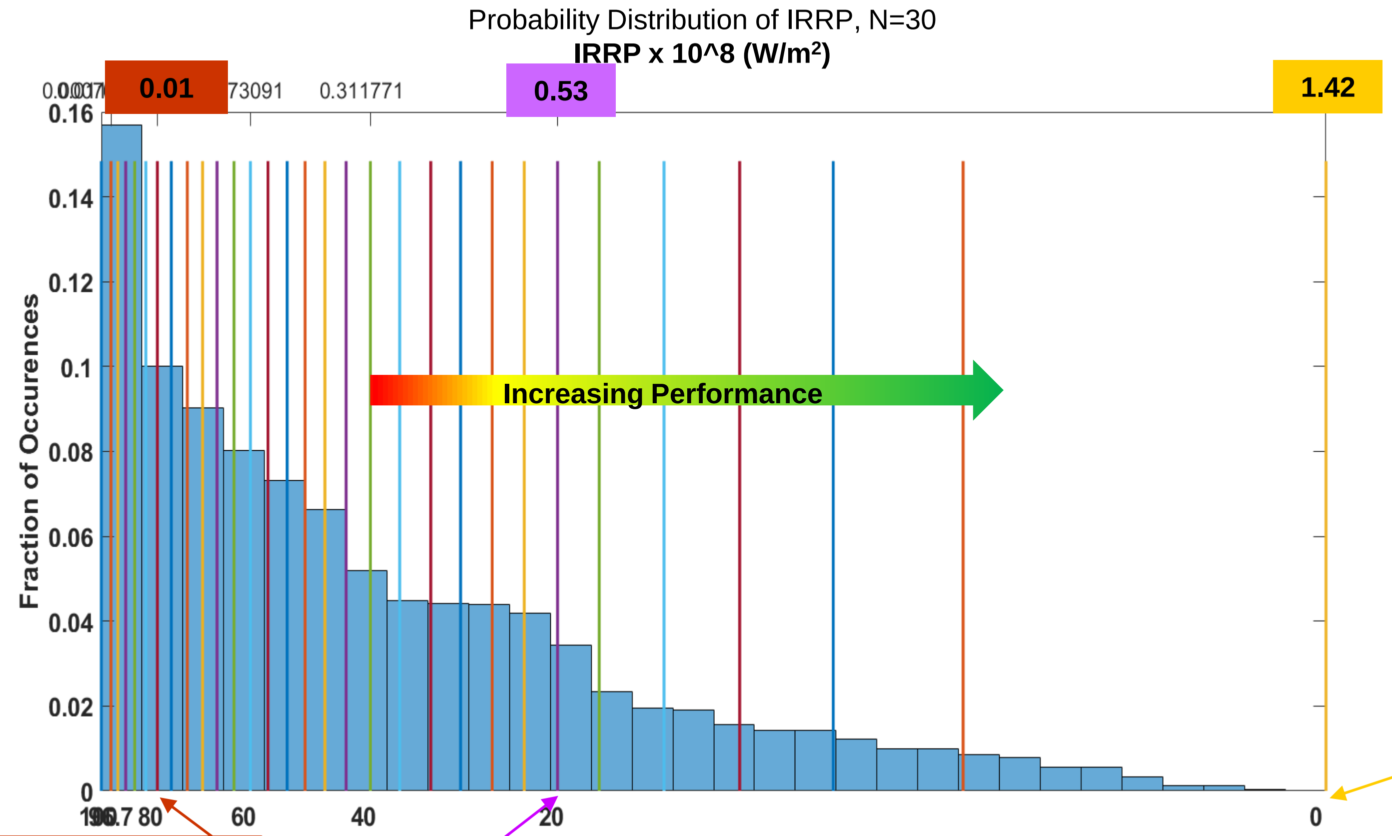
80th %tile: Bad Weather

20th %tile: Good Weather

0th %tile

Black Forest Performance Binning

CUAS2


Probability Distribution of IRRP, N=30

IRRP x 10^8 (W/m²)

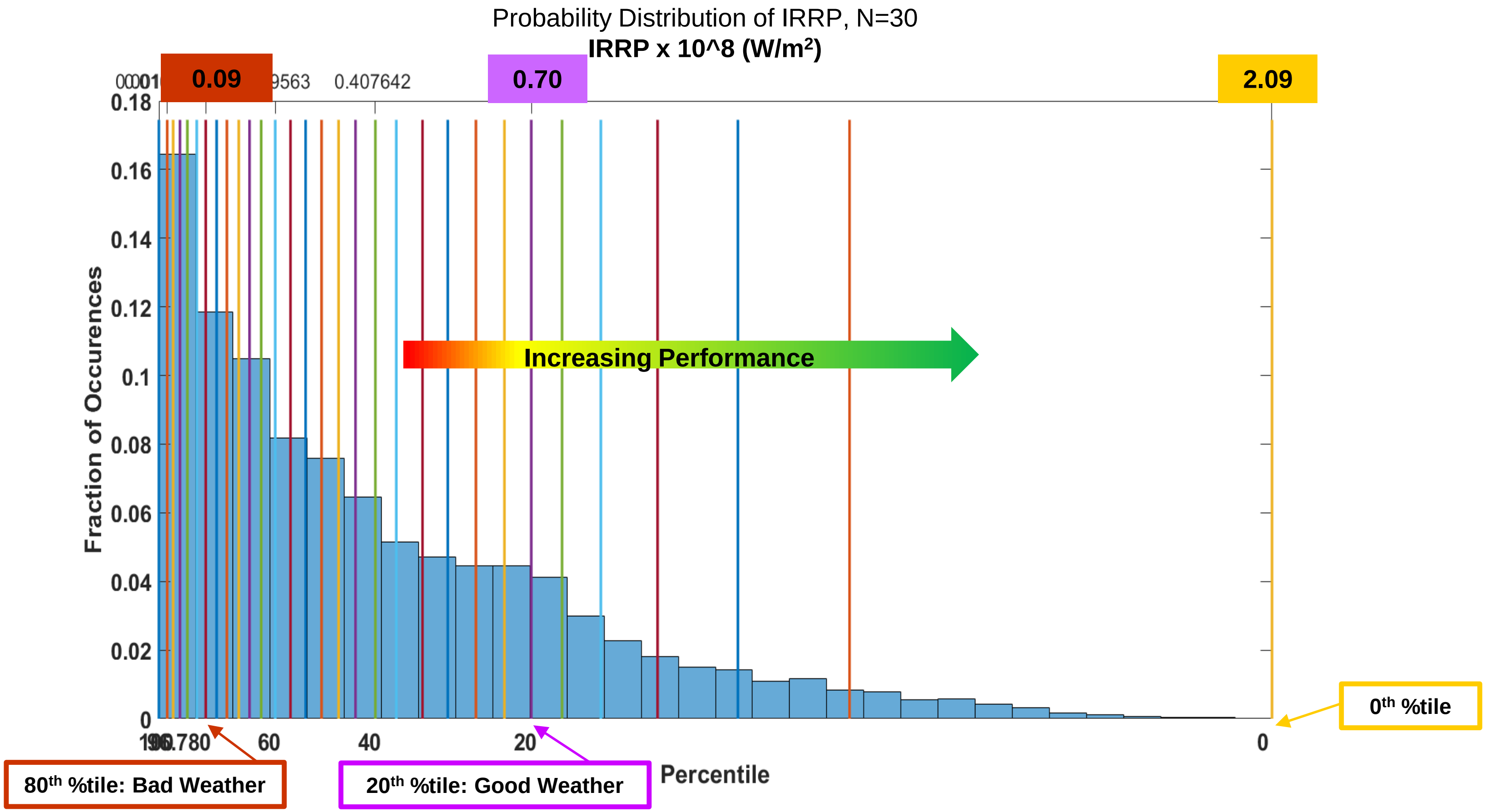
80th %tile: Bad Weather

20th %tile: Good Weather

0th %tile

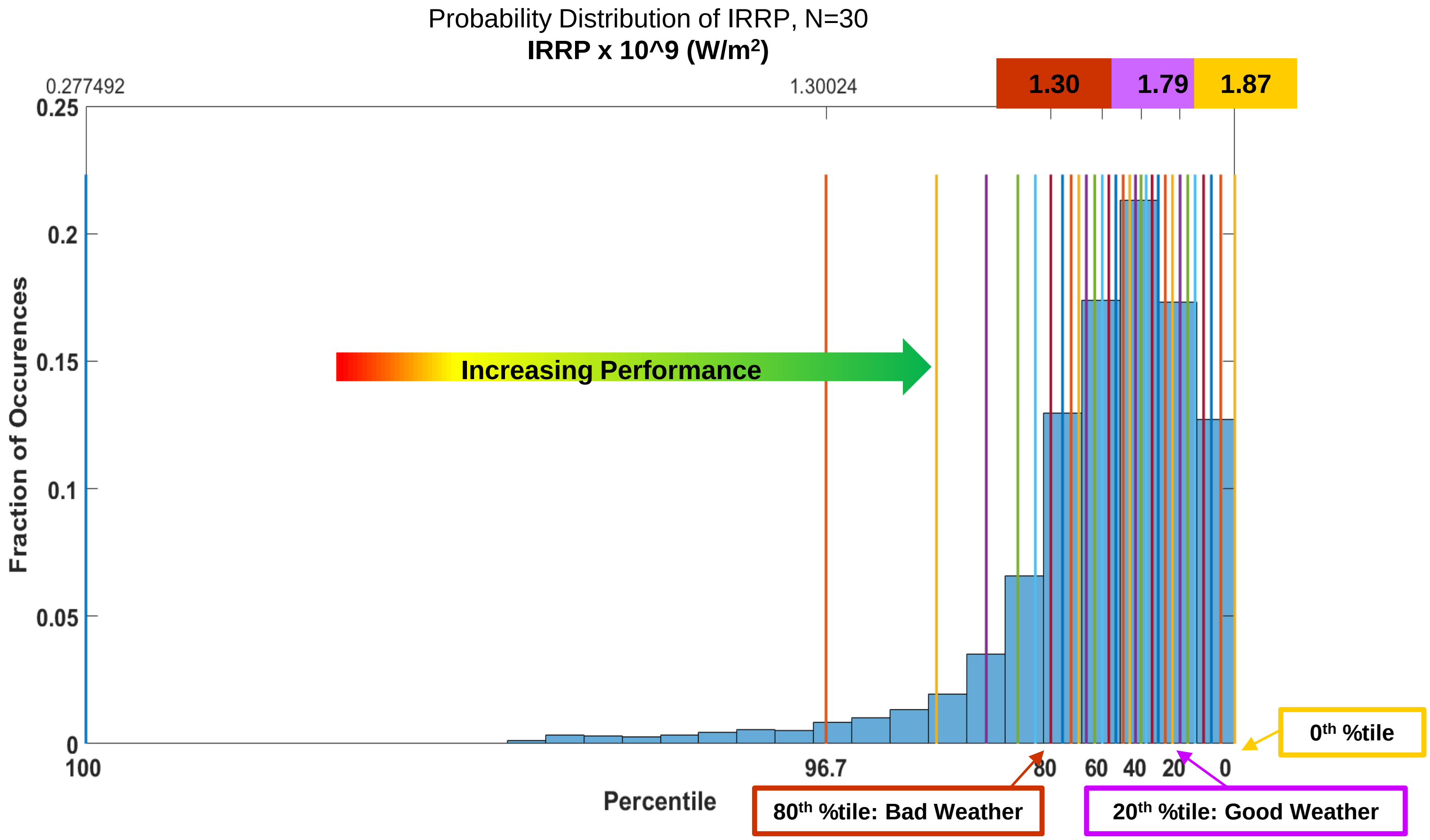
Black Forest Performance Binning

CUAS3



Black Forest Performance Binning

IED1

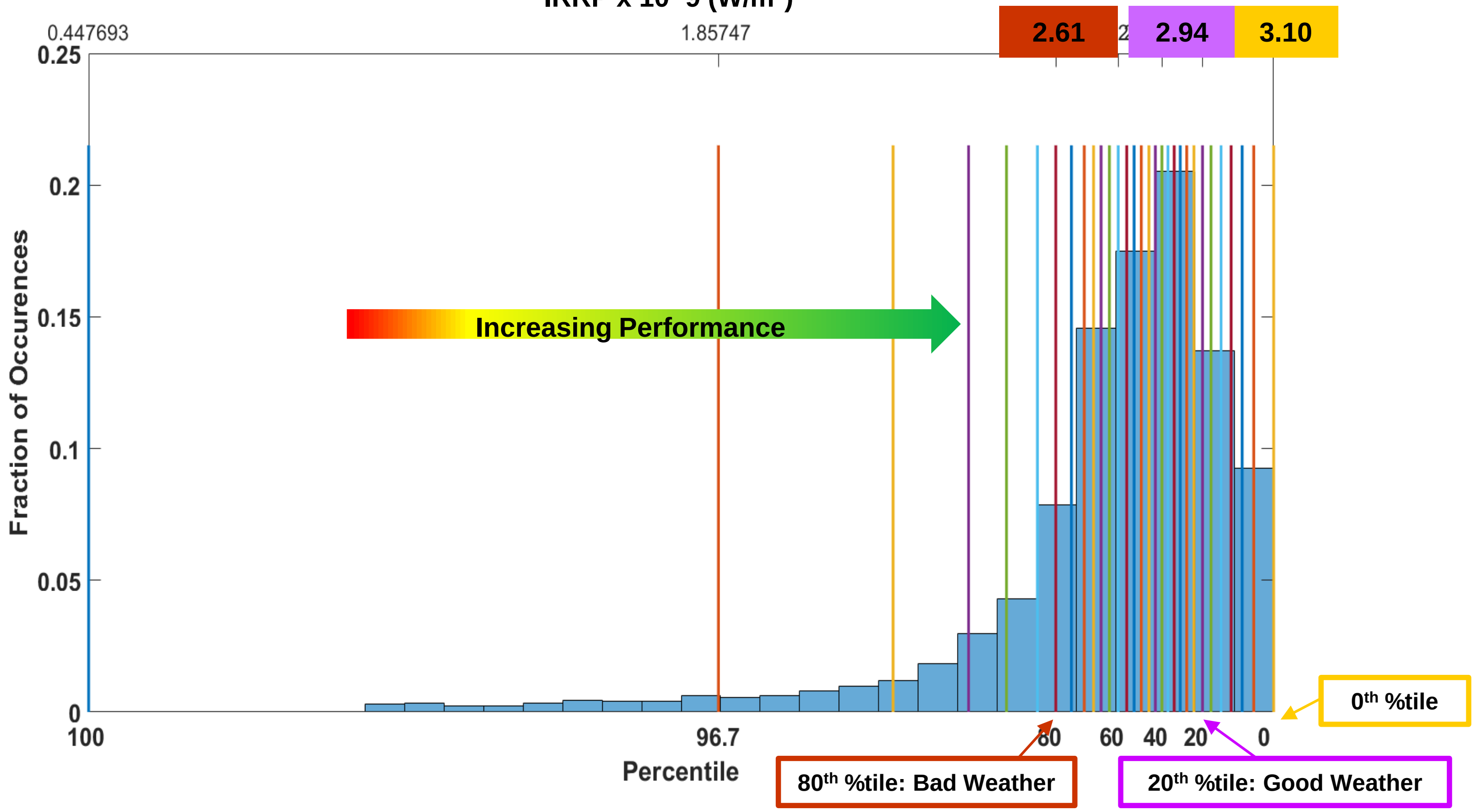


Black Forest Performance Binning

IED2

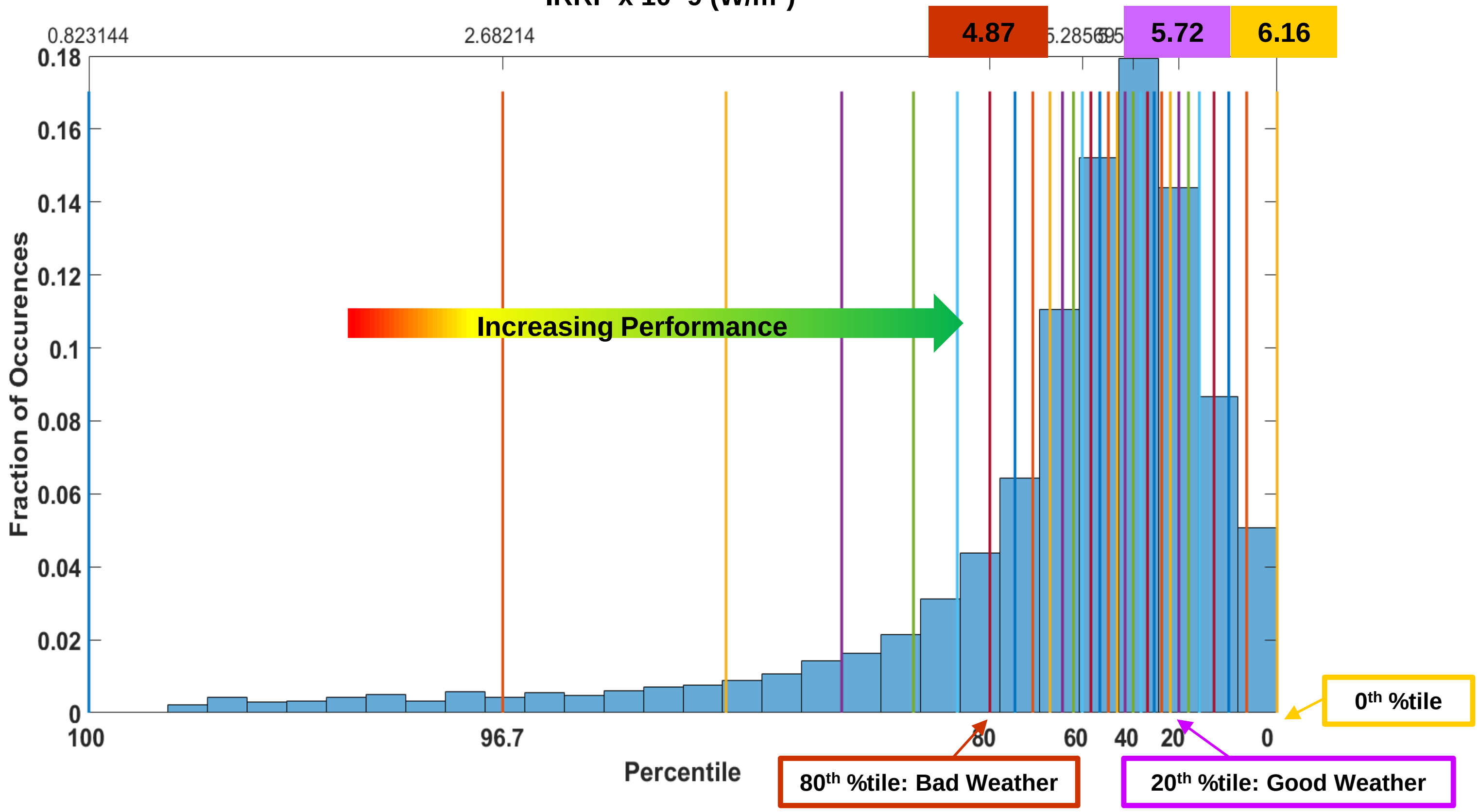
Probability Distribution of IRRP, N=30

IRRP x 10^9 (W/m²)



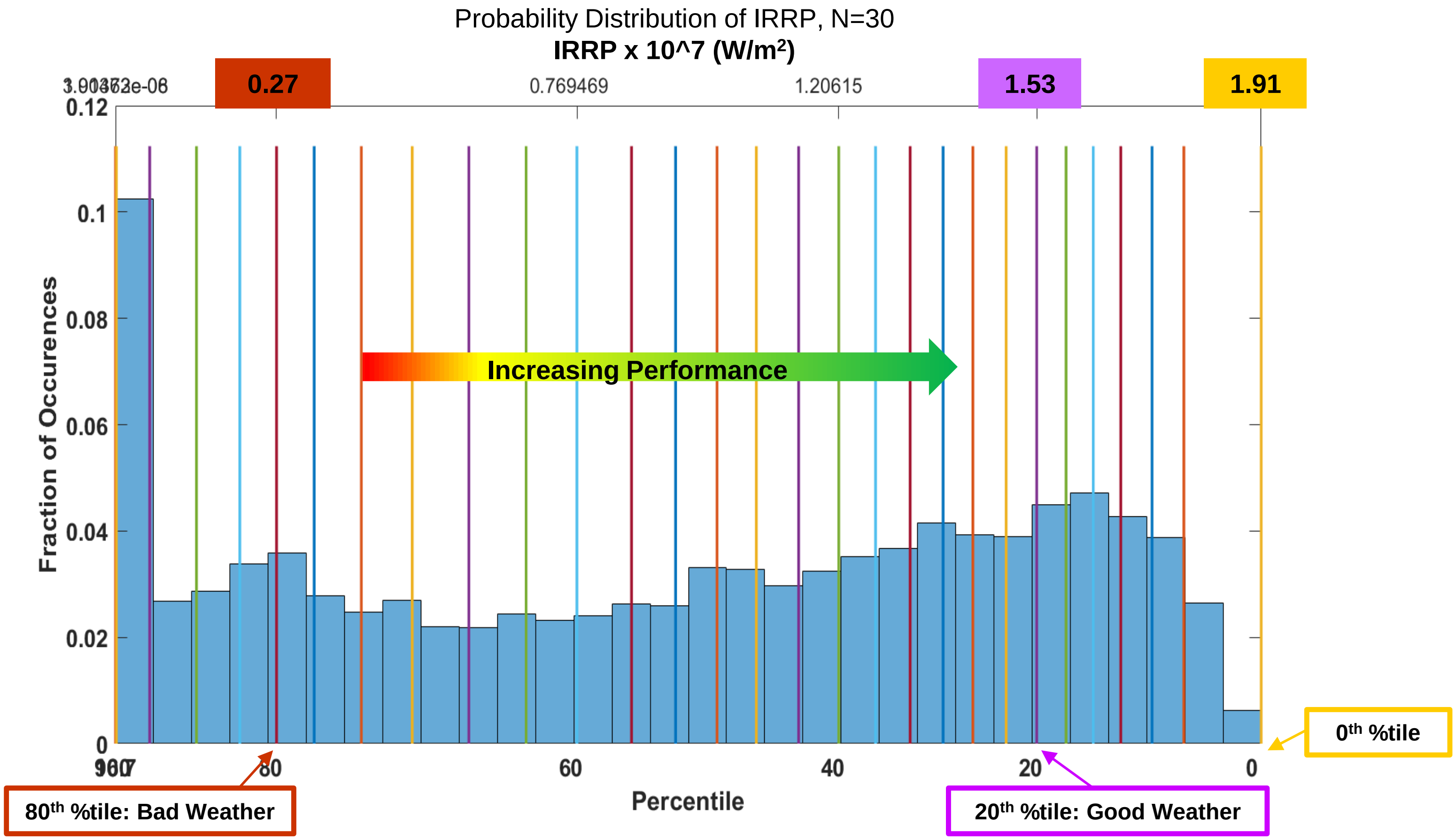
Black Forest Performance Binning

IED3



Black Forest Performance Binning

CRAM1



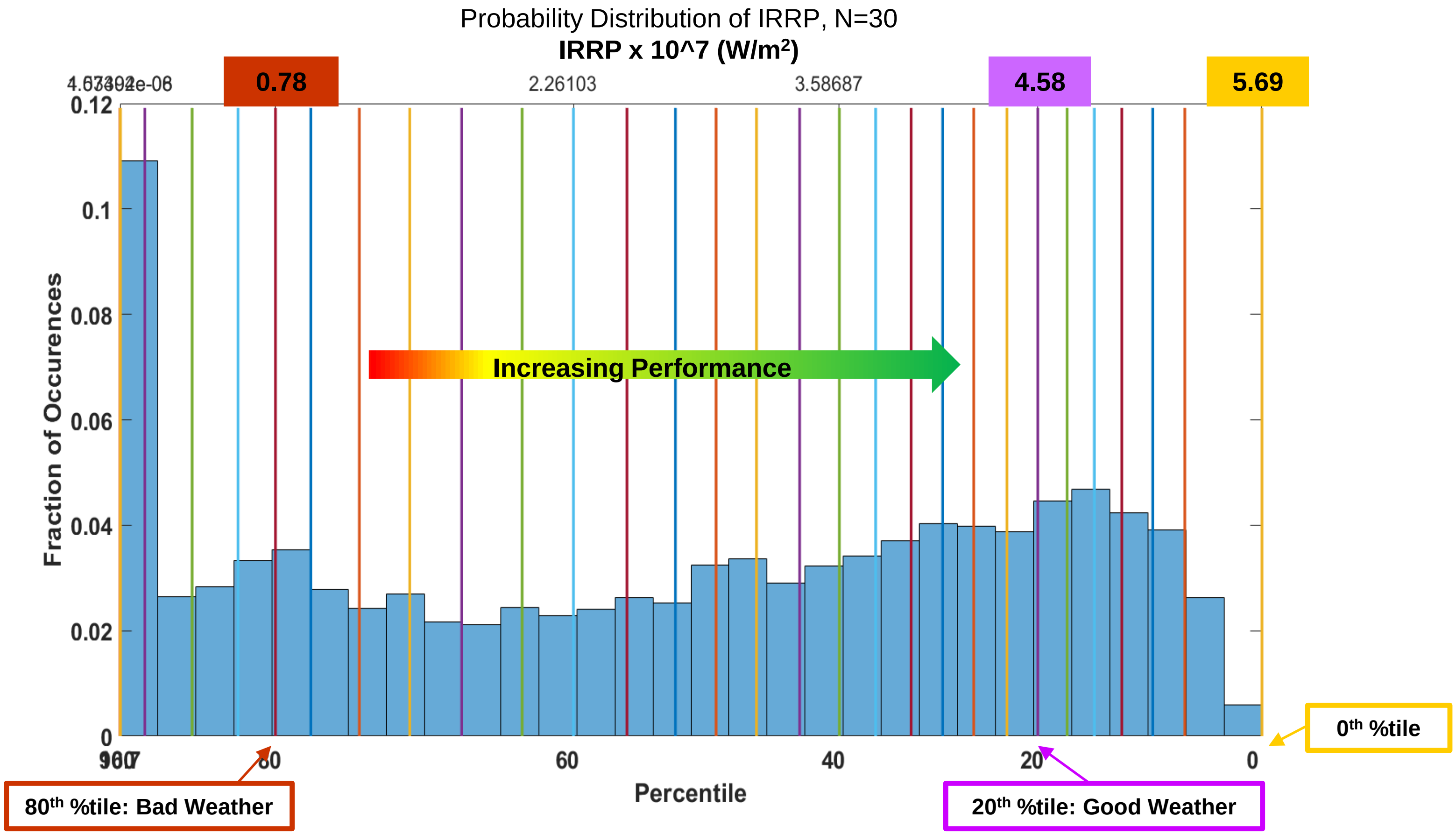
80th %tile: Bad Weather

20th %tile: Good Weather

0th %tile

Black Forest Performance Binning

CRAM2



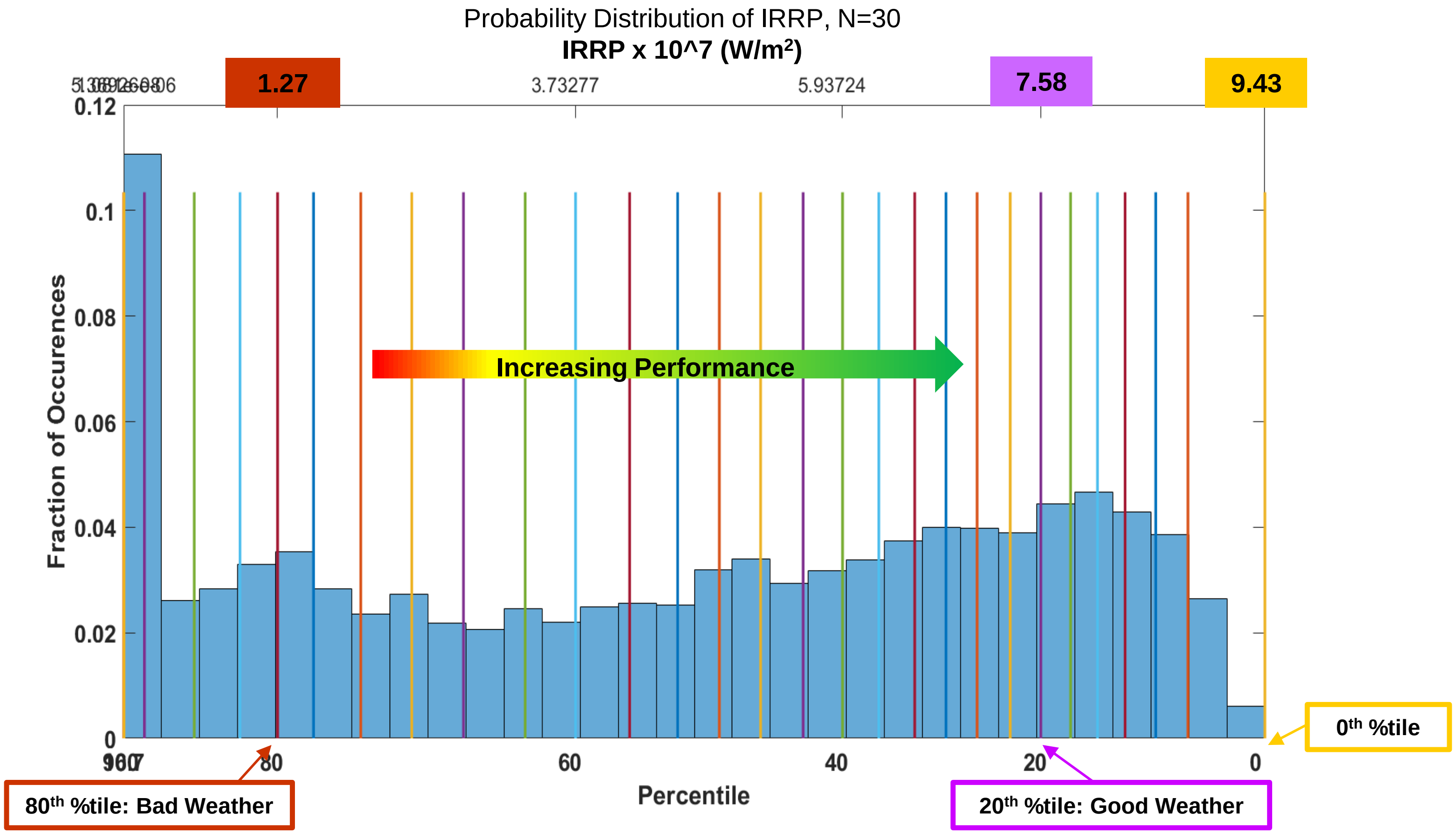
80th %tile: Bad Weather

20th %tile: Good Weather

0th %tile

Black Forest Performance Binning

CRAM3



The Atmosphere

Atmospheric Effects

Summary

The atmosphere has distinct layers mainly defined by temperature lapse rates

Virtually all atmospheric effects on HEL propagation can be traced to absorption, scattering and turbulence

- All three are wavelength or frequency dependent
- All three are generally most degrading near the surface, but don’t always monotonically decrease with height

Thermal blooming is a non-linear effect caused by laser heating due to absorption

Optical turbulence causes spatially and temporally varying irradiance patterns

Some of these effects can be reduced with a beam control system including adaptive optics

Propagation and Adaptive Optics

6. The Atmosphere
    - 6.1 Atmospheric Structure
    - 6.2 Atmospheric Effects
    - 6.3 Adaptive Optics

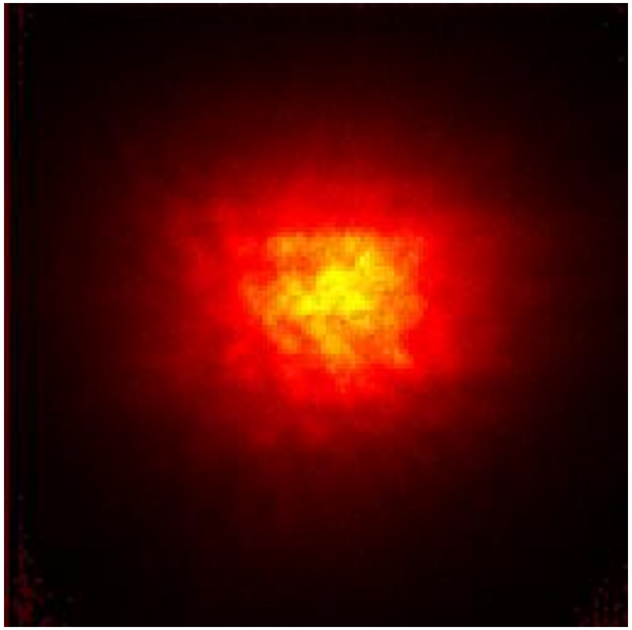
- Goal: Maximize the power of the laser beam concentrated in a small spot on the target, i.e., maximize the Strehl and/or power-in-the-bucket.

- Problem: Atmospheric turbulence, aero-optical flow cause phase aberrations.
  - Random, unpredictable temperature variations cause random variations in the refractive index of the air along the path of the laser beam.
  - HEL beam is distorted, blurring and broadened.
  - Reduction in the power-in-the-bucket.

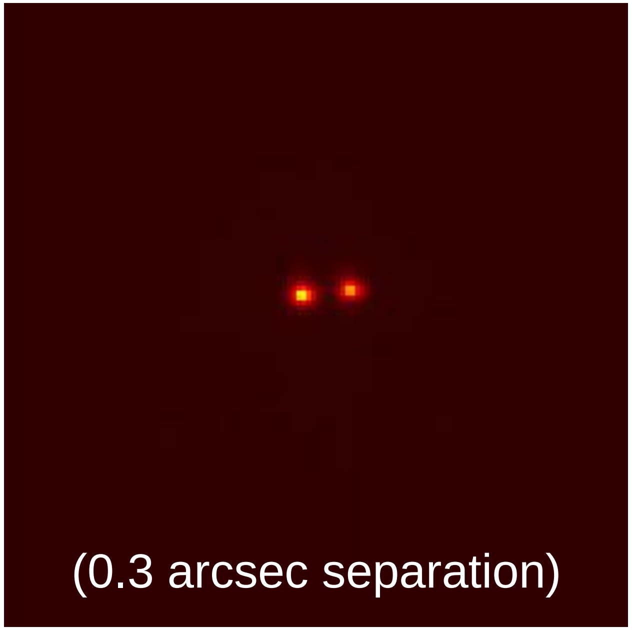
- Solution: Adaptive optics.
  - Wave Front Sensor (WFS): detects the phase aberrations.
  - Reconstructor: controls the DM to compensate for the effects of the phase aberrations induced by atmospheric turbulence.
  - Deformable Mirror (DM): pre warps (compensates) the laser beam so that the effects of the atmosphere undo the warping to form an improved far field spot.

- Result: Increased power-in-the-bucket, i.e., increased power density.

Uncompensated Image



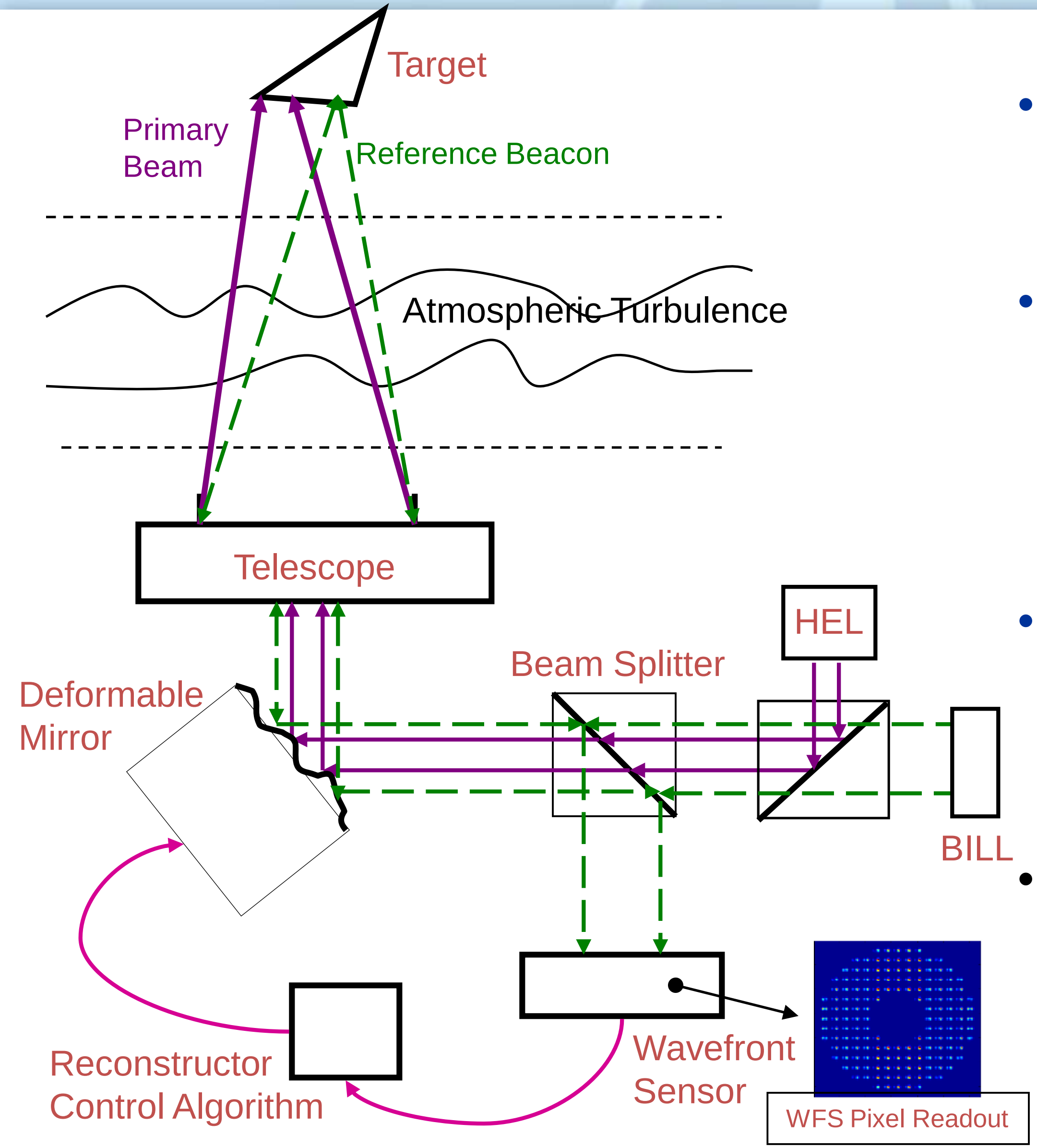
Compensated Image



(0.3 arcsec separation)

First light for the adaptive optics system on the 3.5-m telescope at the Starfire Optical Range (SOR) occurred in September, 1997. This astronomical I Band compensated image of the binary star k-Peg was generated using the 756 active actuator adaptive optics system.

- Beacons: in order to correct for aberrations, a reference source of light, an artificial of natural guide star (beacon) is required. The beacon should be unresolved by the subapertures.
- Signal Strength: The Shack-Hartmann beacon must provide signal strength for all subapertures, an HEL weapon must be prepared to point in any direction, can not rely on natural beacons
- Artificial beacons are used in three ways to create a bright point source bright
  - Target Beacon (active) – must examine pointing requirements, reflectivity and polarization of beacon with the target
  - Rayleigh backscatter in the stratosphere, focus a laser at an altitude above ‘most’ of the atmosphere and measure the backscatter, works up to about 20 km. Signal return can be optimized (polarization is retained), must lead the target
  - Sodium layer excitation, at an altitude of ~92 km, there is a layer of atomic sodium, resonant fluorescence can be used to form a guide star.



- Wavefront Sensor (WFS) detects the phase aberrations from a reference beam.
- Deformable Mirror (DM) or phase corrector corrects the phase aberrations by applying a conjugate phase to the image beam.
- Reconstructor and control algorithm controls the deformation of the DM based on the WFS measurements.
- Laser Weapon System, similar configuration with the science camera replaced by a laser.

Additional Information

- Strehl Ratio S: the ratio of the on axis, expected or measured intensity I_m of the projected beam to the diffraction limited maximum I_0.

$$S = \frac{I_m}{I_o}$$

- Strehl varies from 0 to 1, is a very sensitive metric, used extensively in the community. S=0.8 is considered “well-corrected.” (outstanding)
- Typical Strehl ratios without compensation may be very low, such as 0.05, so even if the AO system improves the Strehl to only 0.2, this is a significant improvement
- Strehl ratio is a point measure only, power density may be more relevant for laser weapons.
- The field in an aperture function has amplitude A(ξ) and phase Φ(ξ):

$$U_a(\xi) = A(\xi)e^{ik\Phi(\xi)}$$

- Non-constant phase Φ(ξ) represents all phase aberrations in the field.
- Fact: Aberrations always reduce the peak intensity of the image, i.e., the Strehl ratio and the power density are always reduced by phase aberrations.

Additional Information

- Phase Aberrations: three major categories of atmospheric induced beam effects,
  - Beam wander (jitter) – random variations of centroid, i.e., tip/tilt, first order phase aberrations.
  - Broadening – Spot size increase beyond diffraction limit, higher-order phase aberrations.
  - Scintillation -- Intensity fluctuations across the beam caused by the phase aberrations propagated over space.

- Correction for phase aberrations: possible with Adaptive Optics
- Correction for intensity fluctuations: not possible with conventional Adaptive Optics. However, for weak turbulence the dominant effect on beam quality is the phase aberrations not the intensity fluctuations

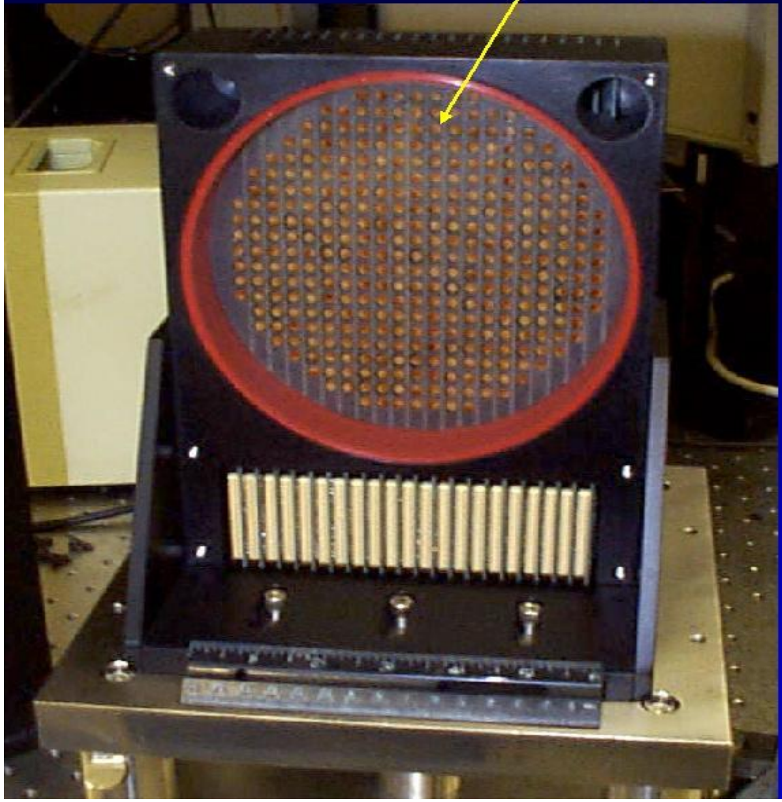
- Not all phase aberrations are caused by atmospheric turbulence.
  - Boundary Layer Turbulence: for airborne platforms, the turbulent air flowing over the airframe also causes phase distortion

- The Fried Parameter, r_0, is also called the atmospheric coherence diameter. Light from the beacon seen at points on the aperture separated by more than this have poor phase correlation.
- More than 87% of the wavefront phase error is removed by removing the tilt/tip modes in the phase aberration.
  - Removing full aperture tilt/tip modes provides drastic relative improvement in the Strehl ratio.
  - Tempting to think that removal of tilt/tip is sufficient correction, this is only true for diameters $D < r_0$ (as for sub-apertures).
  - The ability to correct a system with tilt only is quickly degraded as the ratio D/r_0 grows.
- To obtain a "well-corrected" Strehl ~ 0.6 - 0.8, it may be necessary to correct for a large number of modes when the ratio D/r_0 is large.
  - For $D=r_0$, tilt-removed wavefront variance is only 0.134 rad^2.
  - However, for D = 1m aperture and r_0 = 10cm the tilt-removed wavefront variance is still 6.22 rad^2.
- The Marechal approximation, $S_{HO} = e^{-\varphi^2}$, highlights the problem here:
  - Exp[-0.134 rad^2] = 87% - Pretty Good
  - Exp[-6.22 rad^2] = 2% - Really Not Good

Deformable Mirror

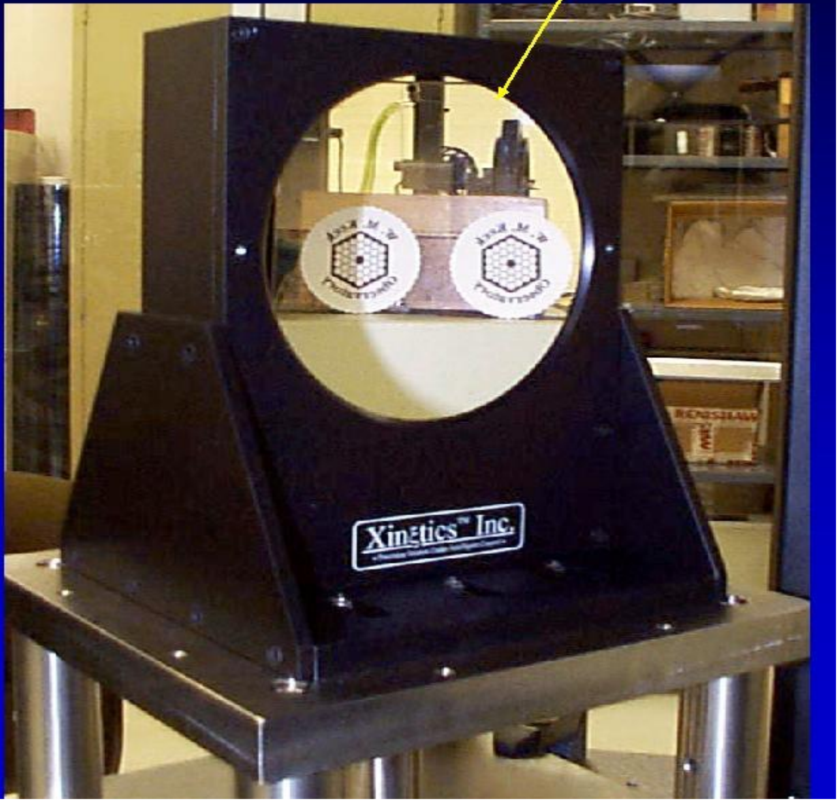
Rear View

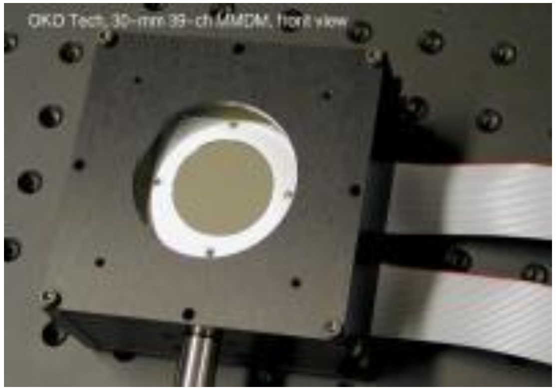
349 Actuators
on 7 mm spacing



Front View

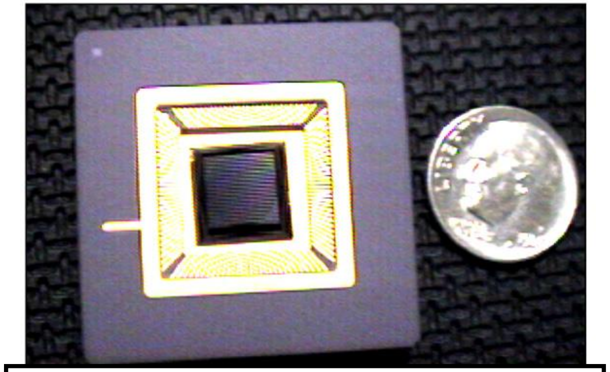
146 mm diameter
clear aperture





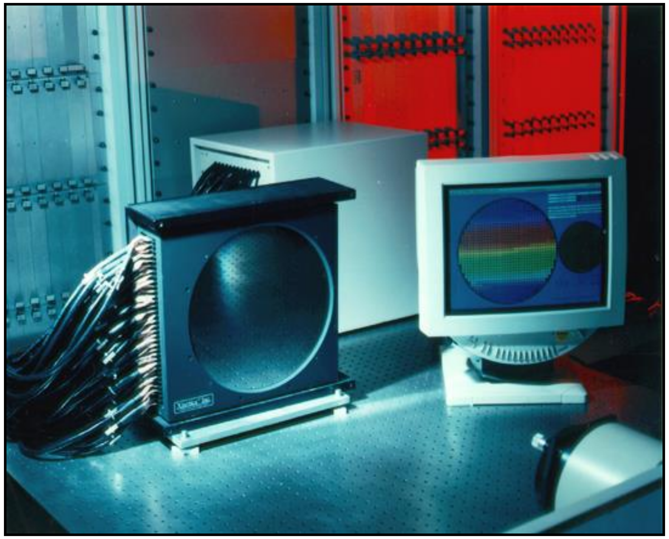
OKO

MEMS Deformable Mirror:
15mm/37 or 19 channels
30 mm/ 39 to 79 channels



Boston Micro-Machines Inc

No hysteresis, 15% influence, 2 μm stroke
2 nm repeatability, 7 kHz bandwith



Xinetics

- ULE Facesheet

-28.8-cm diameter, 2-mm thick polished to 0.045 waves, rms

-Denton FSS-99 silver coating

-PMN Actuators

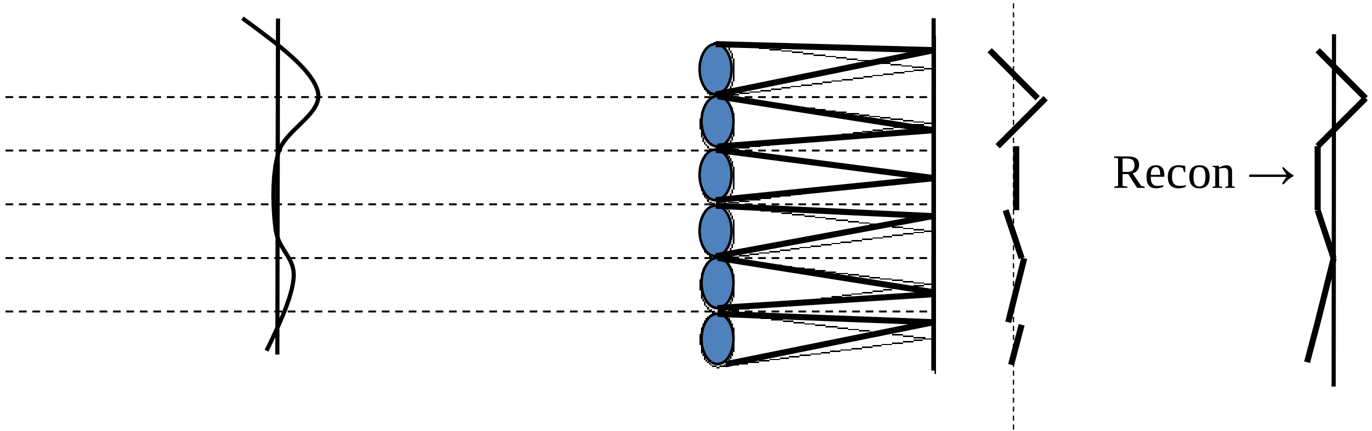
-941 actuators, 9 mm spacing, 810 control actuators

-70 volt bias, ± 30 volt control range, ± 2.4 mm stroke

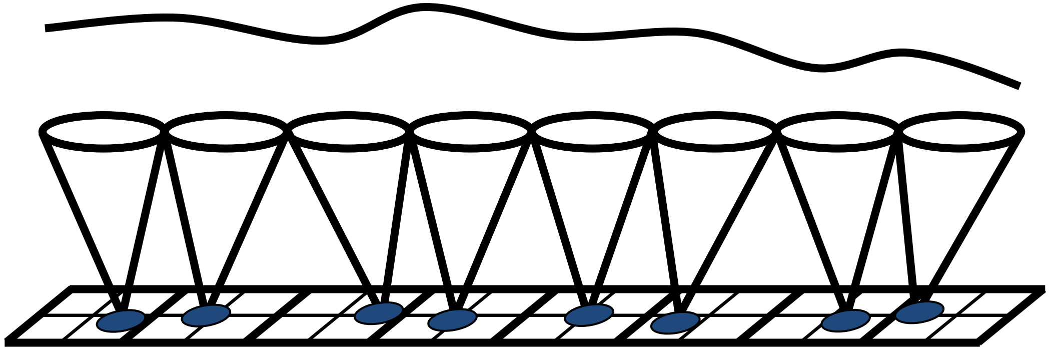
-hysteresis < 1% at 20°C

-nearest-neighbor coupling 9%

Wavefront Sensor/Reconstructor Example in 1-D:



Representative Example in 2-D for sensor, 1-D for lenslets



Key Point – Minimum norm criteria of least squares solution of reconstructor recovers phase so that subapeture corrections are 'linked' together when applied at the DM

- Anisoplanatism, literally, “not in the same plane.”
  - Beacon and object may not share identical effects from turbulence.
  - Light from the beacon may not pass through the same atmospheric turbulence as the light going to the target that must be corrected.

- Types of anisoplanatism (with relevant parameter) and cause
  - Spatial anisoplanatism (Fried parameter r_0): spatial extent of beacon and target beams.
  - Angular anisoplanatism (anisoplanatic angle θ_0) angular separation of beacon and target beams.
  - Temporal anisoplanatism (Greenwood and Tyler frequency $f_{G,}$ $f_{T,}$) temporal separation of beacon and target beams.
  - Focus anisoplanatism difference in measured turbulence due to beacon not located at target
  - Beacon anisoplanatism the beacon extends over more than one isoplanatic patch
  - Chromatic anisoplanatism difference in wavelength between beacon and target beams alters propagation due to dispersion.

- Quality of the compensated beam is degraded because of differences between turbulence experienced by the beacon and the actual turbulence experienced by the primary beam.

Adaptive Optics Summary

- Adaptive Optics (AO) can dramatically improve system performance

- AO corrects higher order phase aberrations
  - An AO system includes: a DM; a WFS; an Illuminator; and, a Reconstructor
  - AO is needed for r_o's much smaller than the primary aperture diameter

SCI-340 Lecture Series Agenda

	First Day	***Presenter***
0800	**Registration**	
0830	**Opening Ceremony & STO Overview**	
0900	**Intro to Lecture Series & HEL Weapon Overview**	**Jacco Dominicus**
1000	**Coffee Break**	
1015	**Intro to LS & HEL Overview cont**	**Jacco Dominicus**
1100	**HEL Weapon Lethality**	**Dominik Pudo**
1300	**Lunch Break**	
1400	**Safe Utilization of HEL Weapons**	**Semih Kumru**
1545	**Coffee Break**	
1615	**End of Day**	
	Second Day	
0830	**Laser Devices & Scaling to High Power**	**Keiron Boyd**
1030	**Coffee Break**	
1045	**Beam Control**	**Nicholas Morley**
1230	**Lunch Break**	
1330	**Propagation & Adaptive Optics**	**Lex van Eijk**
1530	**Coffee Break**	
1545	**HEL Weapons & NATO**	**Lawrence Grimes**
1700	**End of Day**	