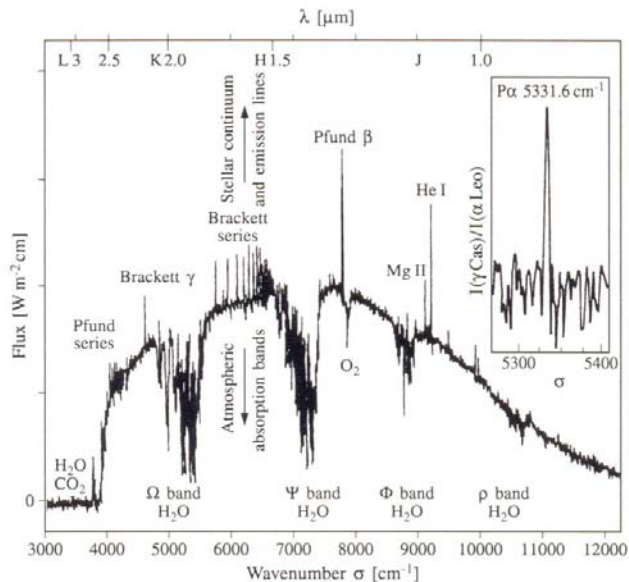# Astronomische Waarneemtechnieken
(Astronomical Observing Techniques)
2nd Lecture: 10 September 2012

1. Atmospheric Layers
2. Absorption
3. Emission
4. Scattering, Refraction & Dispersion
5. Turbulence & Seeing

1. Atmospheric Layers

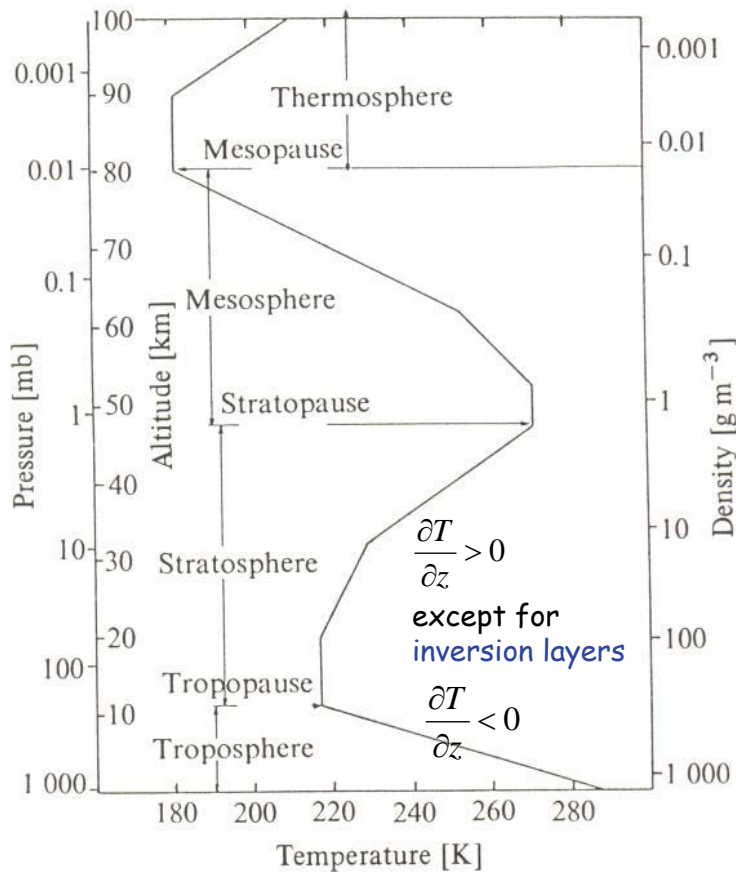Assumption: atmosphere is in local radiative equilibrium and the composition is approximately constant.

The structure can be described by three parameters:

- altitude z

- temperature T(z)

- density $\rho(z)$
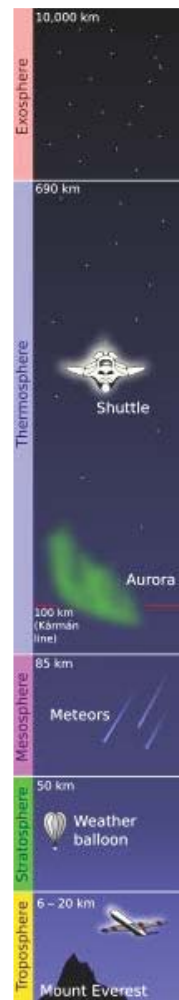
The pressure P(z) can be described by: $P(z) = P_0 e^{-\frac{z}{H}}$

where H = scale height ($H \sim$ 8km near ground).

Vertical Profile

Constituents of the Atmosphere

• <u>Main constituents</u>: O_2 and N_2
  relative constant proportions (78.1% N_2, 20.9% O_2) up to 100 km

• Ozone – absorbs mainly in the UV
  • distribution depends on latitude and season
  • maximum concentration around 16 km height

• CO_2 – important component for (mid)IR absorption
  • mixing independent of altitude (similar to N_2, O_2)

• Ions – varies strongly with altitude and solar activity
  • relevant above 60km where reactions with UV photons occur:

$$O_2 + h\nu \rightarrow O_2^{+*} + e^- \quad \text{and} \quad O_2 + h\nu \rightarrow O^+ + O + e^-$$

  • electron showers along magnetic fields cause Aurora
  • at 100 – 300 km height: $n_e \sim 10^5 - 10^6$ cm^{-3}

• Water vapour – causes very strong absorption bands

2. Absorption of Radiation

Atomic and molecular transitions that cause absorption features:

- pure rotational molecular transitions: H_2O, CO_2, O_3,

- rotation-vibrational molecular transitions: CO_2, NO, CO

- electronic molecular transitions: CH_4, CO, H_2O, O_2, O_3, OH

- electronic atomic transitions: O, N, ...

The attenuation at altitude z_0 is given by:

$$I(z_0) = I_0(\infty) \cdot \exp\left[-\frac{1}{\cos\theta} \sum_i \tau_i(\lambda, z_0) \right]$$

for i absorbing species with an optical depth of $\tau_i(\lambda, z_0) = \int_{z_0}^{\infty} r_i(z)\rho_0(z)\kappa_i(\lambda)dz$

(θ is the zenith distance; κ is the absorption coefficient; ρ_0 is the mass density of air, and $r_i(z)$ the mixing ratio).

Atmospheric Bands
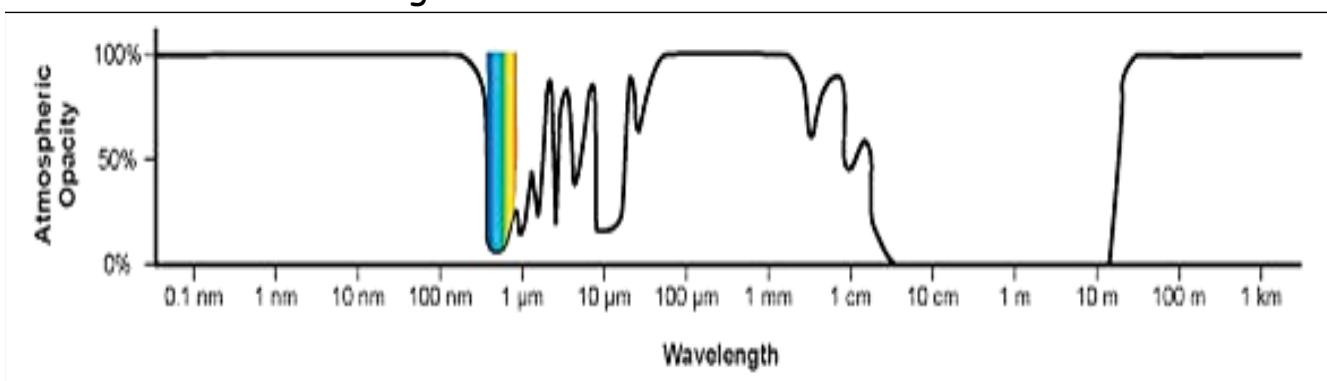
Two cases of absorption:
- total absorption → atmospheric transmission windows
- partial absorption → reduced transmission due to narrow telluric* absorption features

*Telluric = related to the Earth; of terrestrial origin

The atmospheric opacity defines the atmospheric transmission bands – and thus the wavelengths that are accessible to observations

Ground based astronomy is limited to visible, near/mid-IR and radio wavelengths.
Space astronomy provides access to γ-rays, X-rays, UV, FIR, sub-mm
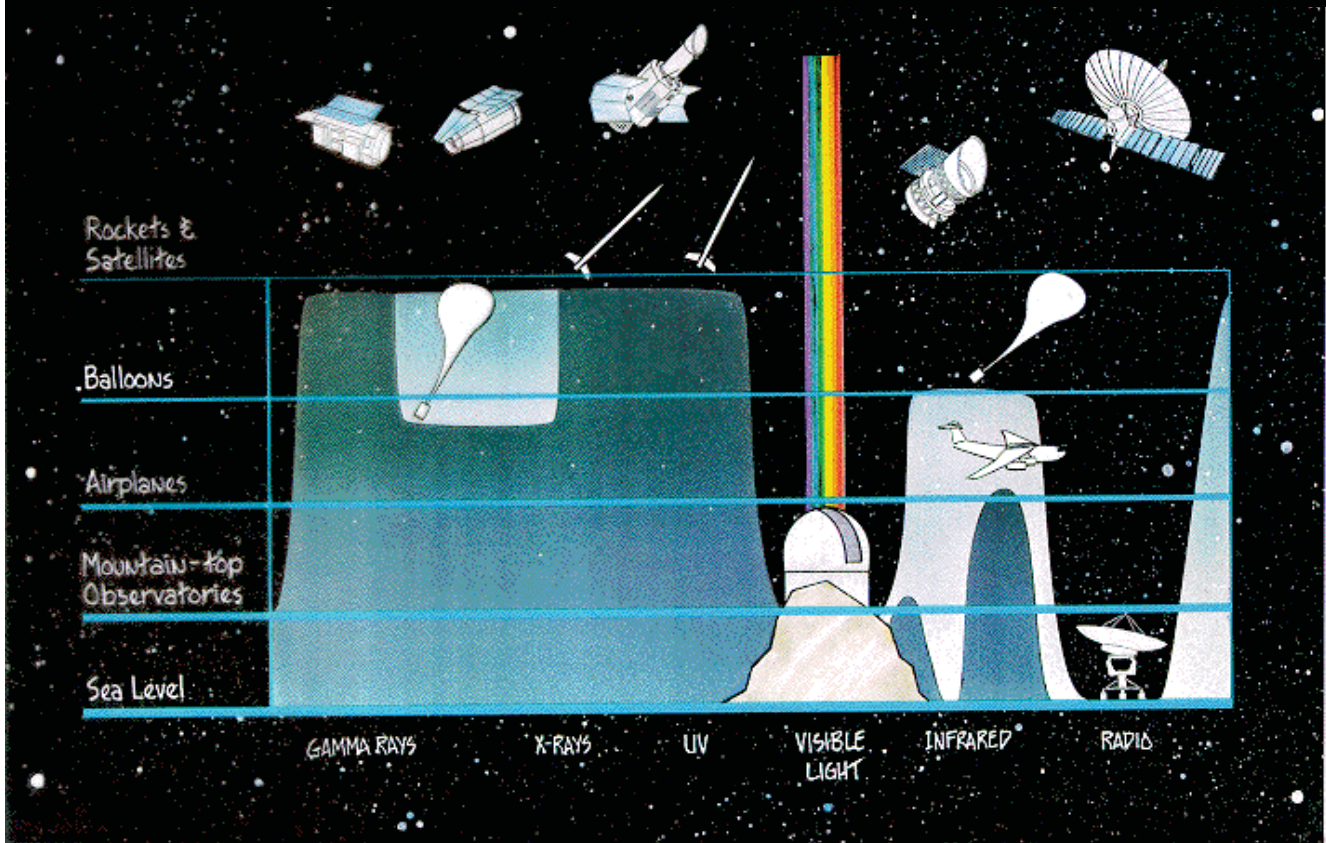
Absorption by Water Vapour
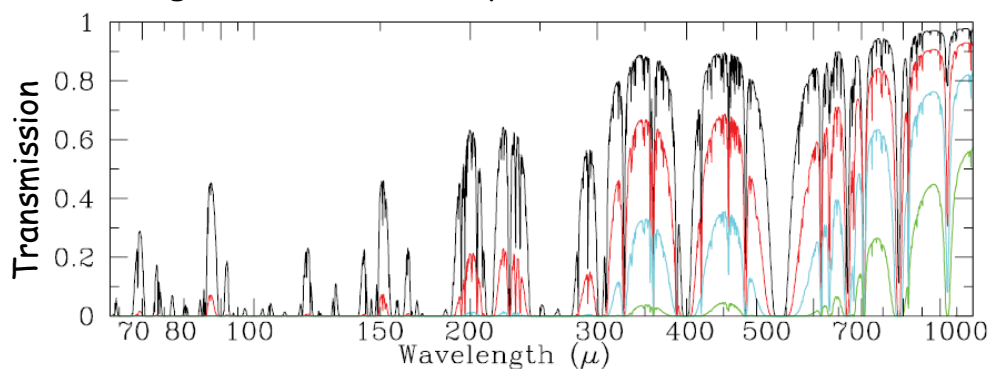
The water vapor is a strong function of T and z.

The precipitable water vapor (PWV) is the depth of the amount of water in a column of the atmosphere if all the water in that column were precipitated as rain.

The amount of PWV above an altitude z_0 is:

$$w(z_0) = \int_{z_0}^{\infty} N_{H_2O} \, dz \, , \qquad \text{where} \qquad N_{H_2O}[\text{m}^{-3}] = 4.3 \times 10^{25} \frac{P}{P_0} \frac{T}{T_0} r(z)$$
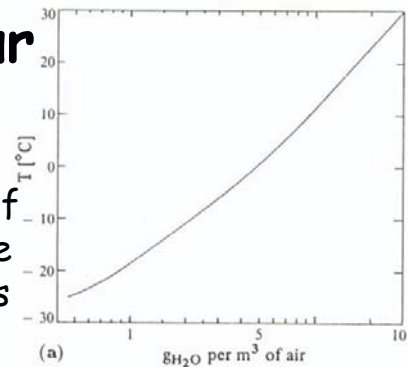
Scale height for PWV is only ~3 km → observatories on high altitudes

0.1 mm PWV
0.4 mm PWV
1.0 mm PWV
3.0 mm PWV

Side note: SOFIA

FIR/sub-mm astronomy is also possible from airplanes, e.g. the
Stratospheric Observatory for Infrared Astronomy (SOFIA)

3. Atmospheric Emission

A. Fluorescent Emission

Fluorenscence = recombination of electrons with ions.

The recombination probability is low; takes several hours → night time

- Produces both continuum + line emission = airglow

- Occurs mainly at ~ 100 km height

- Main sources of emission are: O I, Na I, O_2, OH (←NIR), H

The emission intensity is measured in Rayleigh:

$$1\,\text{Rayleigh} = 10^6\,\text{photons cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1} = \frac{1.58\cdot10^{-11}}{\lambda[\text{nm}]}\,\text{W cm}^{-2}\,\text{sr}^{-1}$$

B. Thermal Emission

Up to 60 km is the atmosphere in local thermodynamic equilibrium (LTE), i.e., the excitation levels are thermally populated.

Calculating the specific energy received requires a full radiative transfer calculation (see below), but for $\tau \ll 1$ one can use the approximation:
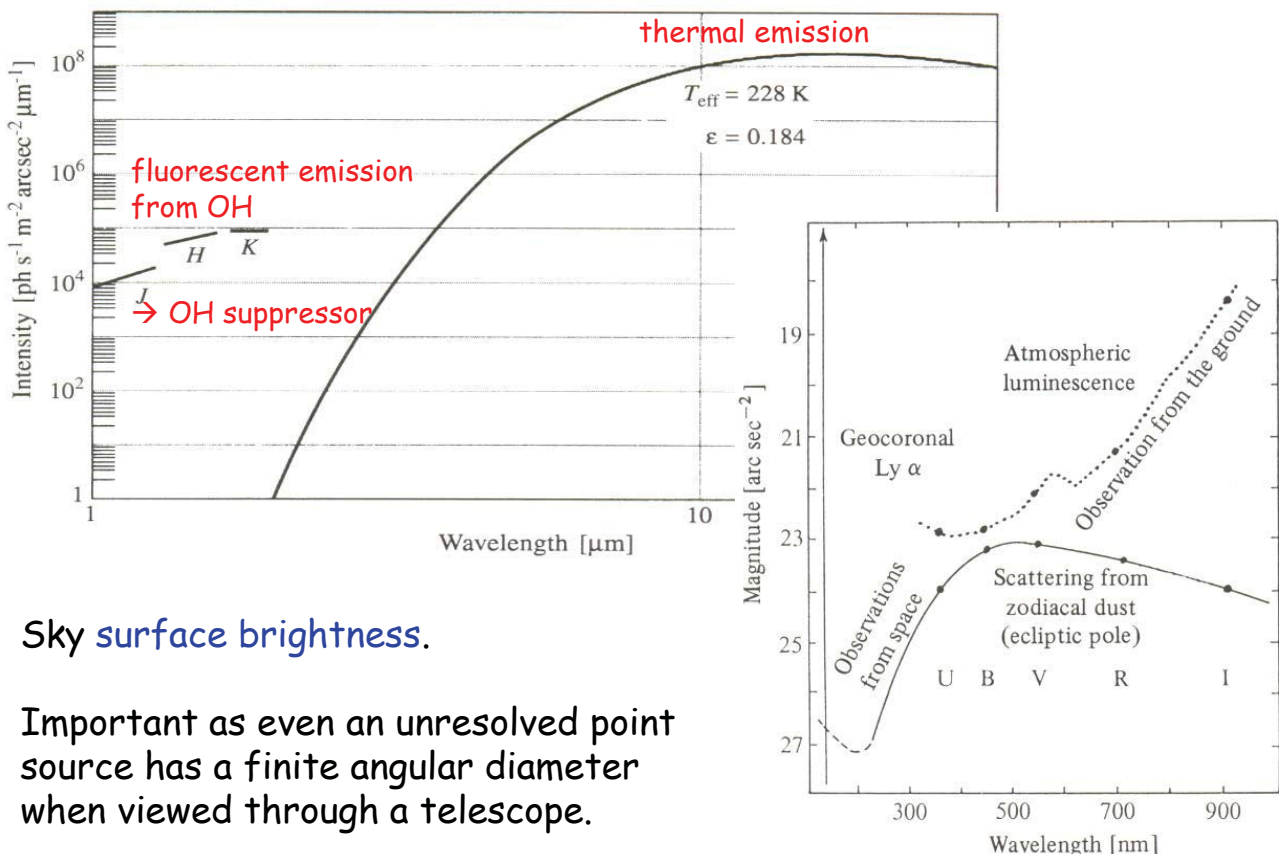
$$I_\lambda(z) = \tau_\lambda B_\lambda(\overline{T}) \frac{1}{\cos\theta}$$

where $B(\overline{T})$ is the Planck function at the mean temperature of the atmosphere.

For $\overline{T}$ = 250 K and θ = 0:

Spectral band	L	M	N	Q
Mean wavelength [μm]	3.4	5.0	10.2	21.0
Mean optical depth τ	0.15	0.3	0.08	0.3
Magnitude [arcsec^{-2}]	8.1	2.0	−2.1	−5.8
Intensity [Jy arcsec^{-2}][a]	0.16	22.5	250	2 100

Fluorescent and Thermal Emission

thermal emission

T_{eff} = 228 K

ε = 0.184

fluorescent emission from OH

→ OH suppressor
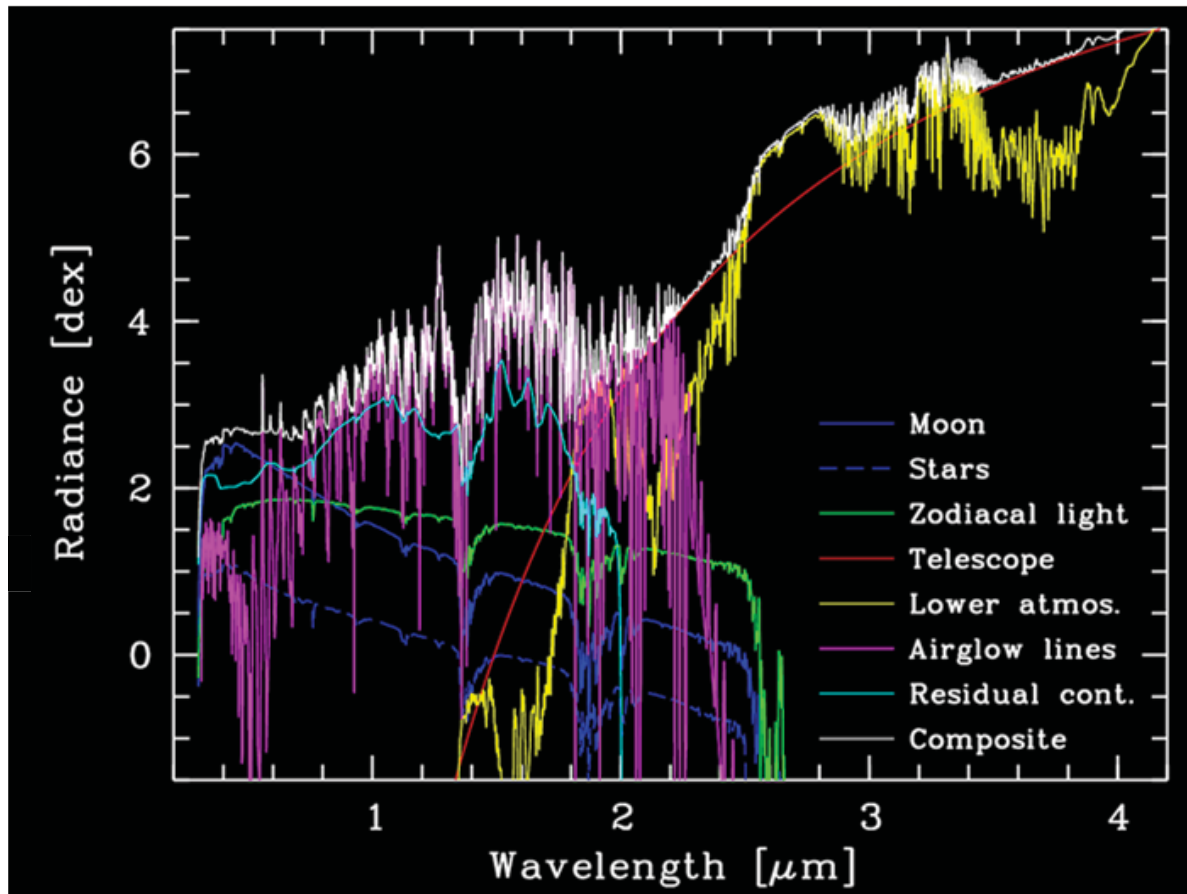
Sky surface brightness.

Important as even an unresolved point source has a finite angular diameter when viewed through a telescope.

Total Emission in the near-IR

4. Scattering, Refraction and Dispersion

A. Scattering by Air Molecules

Molecular scattering in the visible and NIR is Rayleigh scattering given by:

$$\sigma_R(\lambda) = \frac{8\pi^3}{3} \frac{\left(n^2 - 1\right)^2}{N^2 \lambda^4}$$

where N is the number of molecules per unit volume and n is the refractive index of air $(n-1 \sim 8 \cdot 10^{-5}\ P/T)$.

Remember, Rayleigh scattering is not isotropic: $I_{scattered} = I_0 \frac{3}{16\pi} \sigma_R \left(1 + \cos^2\theta\right) d\omega$

B. Aerosol Scattering

Aerosols (like sea salts, hydrocarbons, volcanic dust) are much bigger than air molecules → Rayleigh scattering does *not* apply.

Instead, scattering is described by Mie's theory (from classical electrodynamics, using a "scattering efficiency factor" Q):
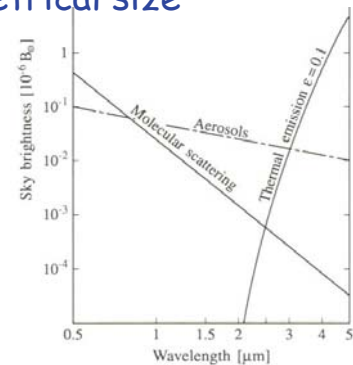
$$Q_{\text{scattering}} = \frac{\sigma_M}{\pi a^2} = \frac{\text{scattering cross section}}{\text{geometrical cross section}}$$

If a ≫ λ then $Q_{\text{scattering}} \sim Q_{\text{absorption}}$ and:
  - the scattered power is equal to the absorbed power
  - the effective cross section is twice the geometrical size

If a ~ λ then $Q_s \propto 1/\lambda$ (for dielectric spheres):
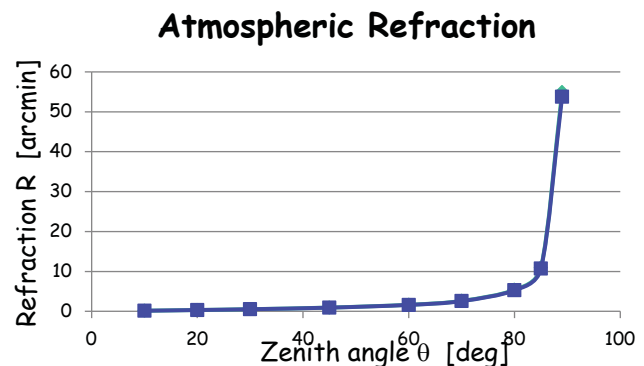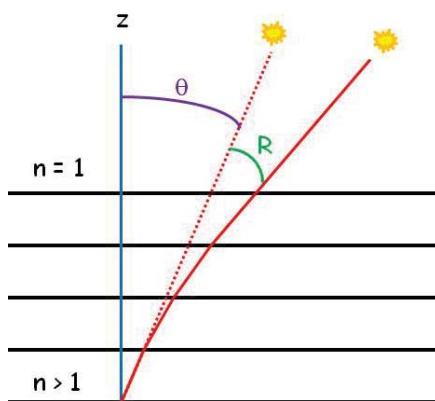 - the scattered intensity goes with 1/λ

Atmospheric Refraction

Due to atmospheric refraction, the *apparent* location of a source is significantly altered (up to half a degree near the horizon)
→ telescope pointing model.

Refraction $R = (n(\lambda)-1)\tan\theta$

Atmospheric Refraction

Note that the refractive index of air depends on the wavelength λ:

$$[n(\lambda)-1]\times 10^6 = 64.328 + \frac{29498.1}{146 - \frac{1}{\lambda_0^2}} + \frac{255.4}{41 - \frac{1}{\lambda_0^2}}$$
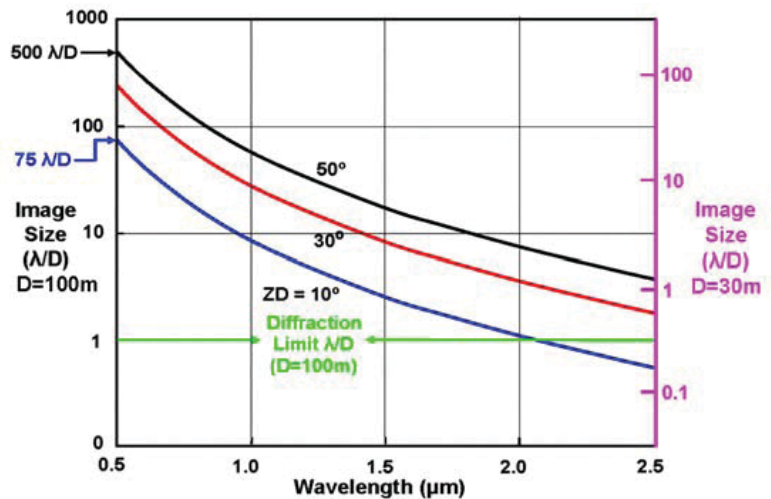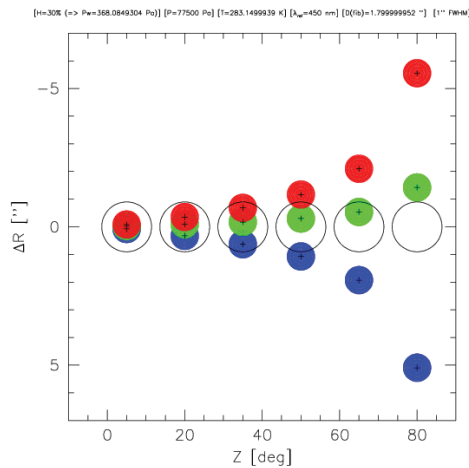
(valid for dry air, 1 atm pressure, T ~ 290K and λ_0 in [µm]).

Atmospheric Dispersion

Dispersion: The elongation of points in broadband filters due to n(λ)
[$\rightarrow$ "rainbow"].
The magnitude of the dispersion is a strong function of airmass and wavelength.

No problem is dispersion < λ/D $\leftarrow$ o.k. for small or seeing limited telescopes, but big problem for large diffraction limited telescopes
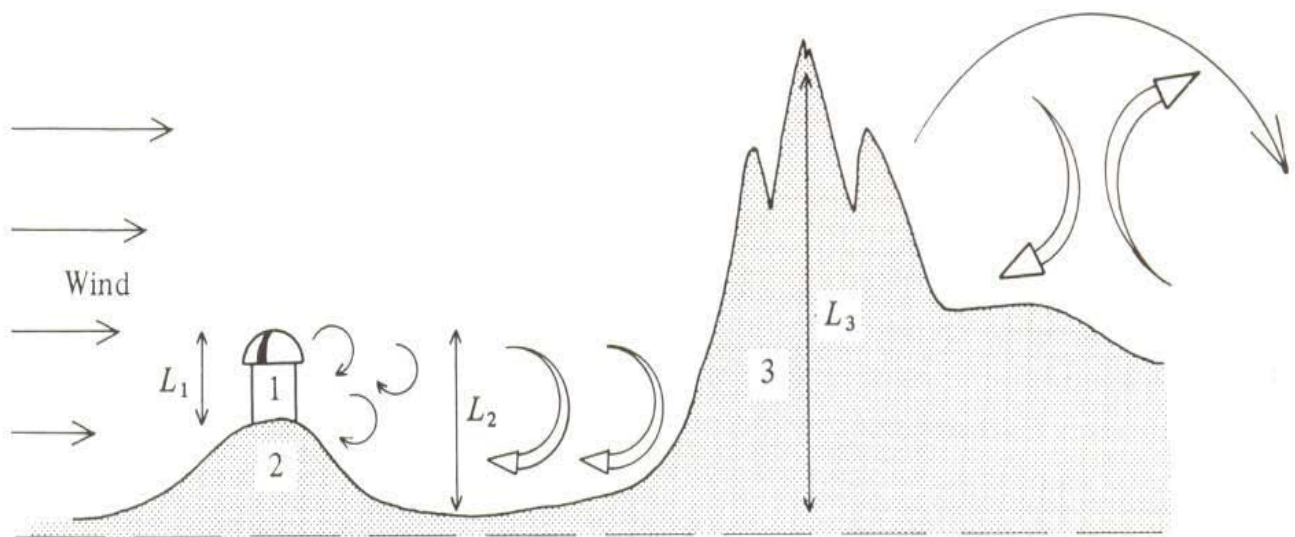

Atmospheric Dispersion Corrector

To counterbalance atmospheric dispersion use:
1. a refractive element (e.g., prism)
2. a second prism (different material with different dispersion) to maintain the optical axis
3. use a second (identical) double prism assembly to adjust the strength of the correction for different zenith angles.
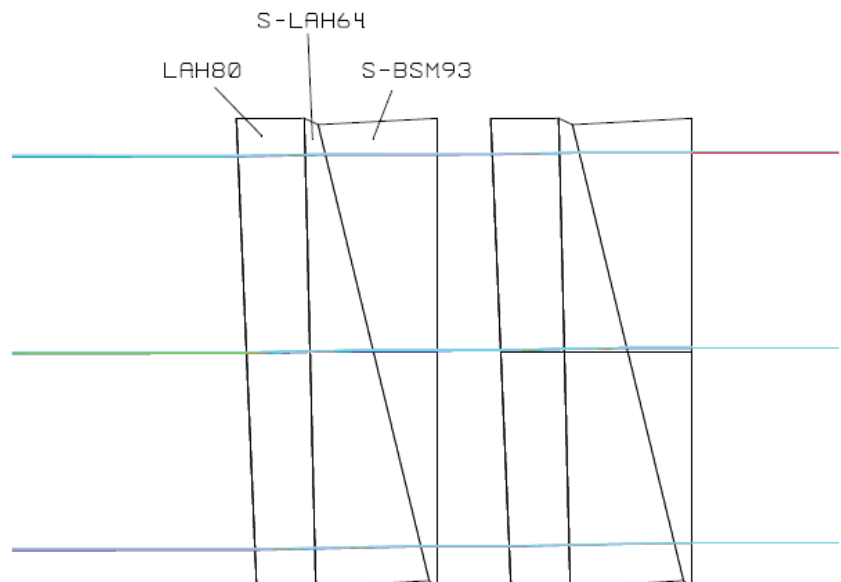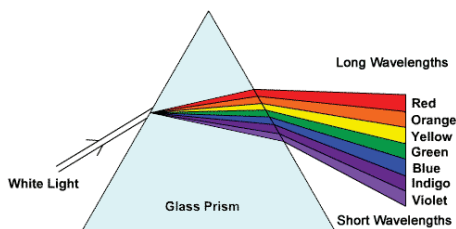
5. Atmospheric Turbulence

The scales L_1, L_2, L_3 are characteristic of the outer (external) scales of turbulence caused by the wind around the obstacles 1, 2, 3.

The Reynolds Number

Turbulence develops in a fluid when the Reynolds number *Re*

$$\mathrm{Re} = \frac{\rho V L}{\mu} = \frac{VL}{\nu}$$

exceeds a critical value.

> *V* is the flow velocity
> μ is the dynamic viscosity
> ν the kinematic viscosity of the fluid (ν_{air}=1.5·10^{-5} m^2 s^{-1})
> *L* the characteristic length, e.g. a pipe diameter.

At Re ~ 2200 the transition from laminar to turbulent flow occurs.

Example: wind speed ~ 1 m/s, L = 15m → Re = 10^6 → turbulent!

The Power Spectrum of Turbulence

The kinetic energy of large scale (~L) movements is gradually transferred to smaller and smaller scales, down to a minimum scale length l_0, at which the energy is dissipated by viscous friction.
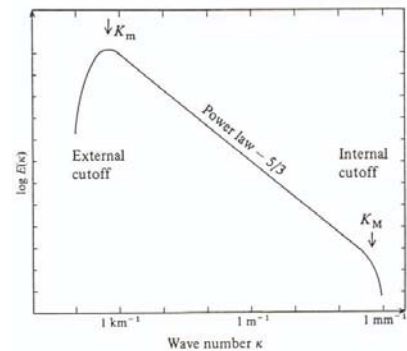
The local velocity field can be decomposed into spatial harmonics of the wave vector κ.
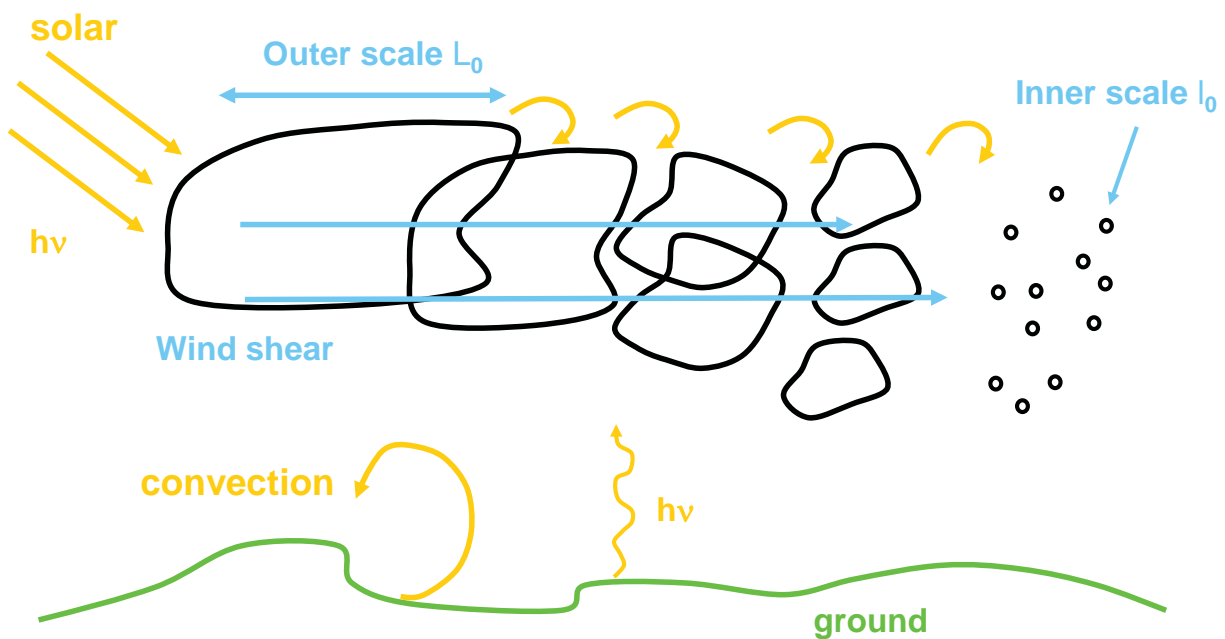The reciprocal value $1/\kappa$ represents the scale under consideration.

The mean 1D spectrum of the kinetic energy, or Kolmogorov spectrum, is:

$$E(\kappa) \propto \kappa^{-5/3}$$

where l_0 is the inner scale, L_0 the outer scale of the turbulence, and $L_0^{-1} < \kappa < l_0^{-1}$

Kolmogorov Turbulence

Air Refractive Index Fluctuations

Winds mix layers of different temperature → fluctuations of temperature T → fluctuations of density ρ→ fluctuations of refractive index n.

Of interest: difference between n(r) at point r and n(r+ρ) at a nearby point r+ρ. The variance of the two values is given by:

$$D_n(\rho) = \left\langle \left| n(r) - n(r+\rho) \right|^2 \right\rangle = C_n^2 \rho^{2/3}$$

where $D_n(\rho)$ is the index structure function and C_n^2 is the index structure coefficient or structure constant of the refractive index.

Air Refractive Index Fluctuations (2)

Usually, one is only interested in the *integral* of fluctuations along the line of sight: $C_n^2 \cdot \Delta h$.

Typical value: $C_n^2 \cdot \Delta h \sim 4 \cdot 10^{-13}$ cm$^{1/3}$ for a 3 km altitude layer

But: there are always several layers of turbulence
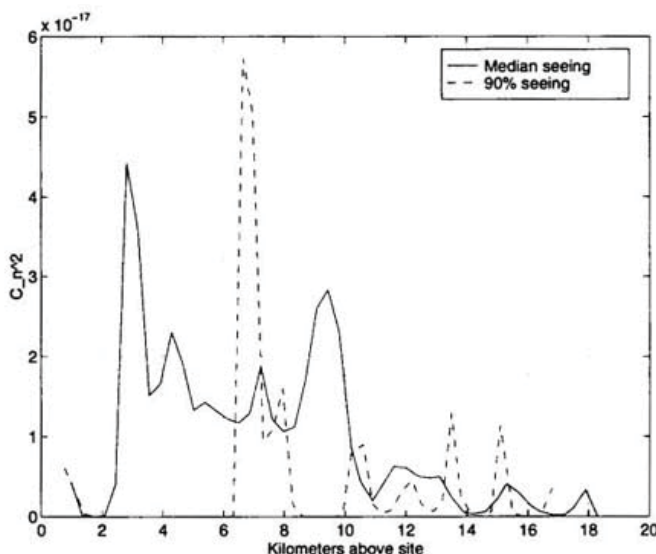
Median seeing conditions on Mauna Kea are taken to be $r_o \sim 0.23$ meters at 0.55 microns. The 10% best seeing conditions are taken to be $r_o \sim 0.40$ meters. Figure taken from a paper by Ellerbroek and Tyler (1997).
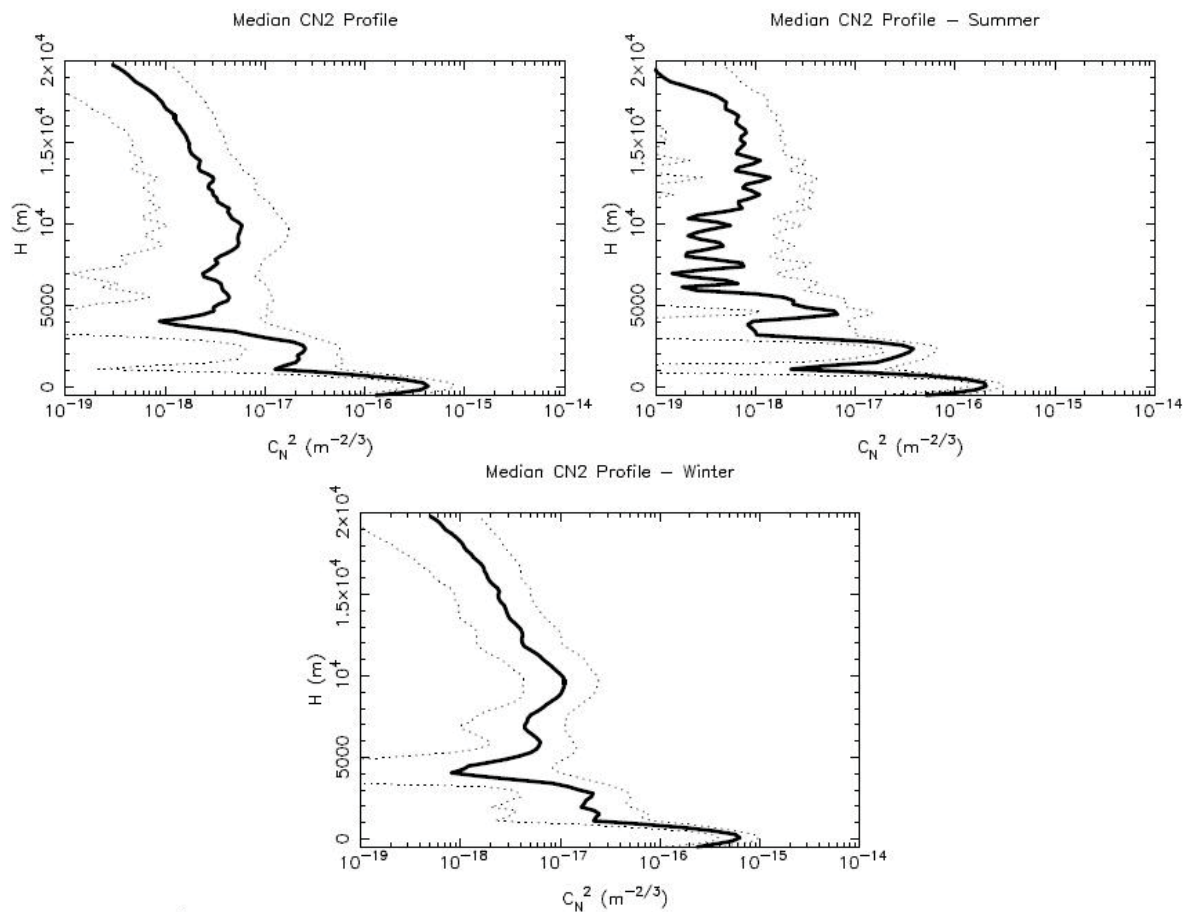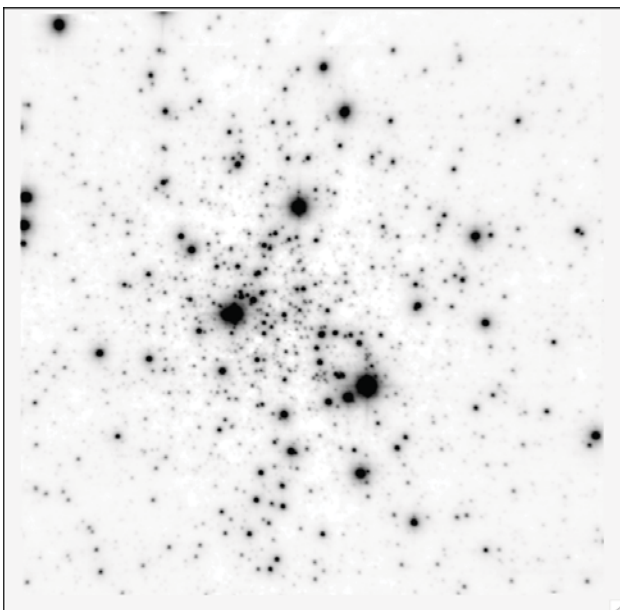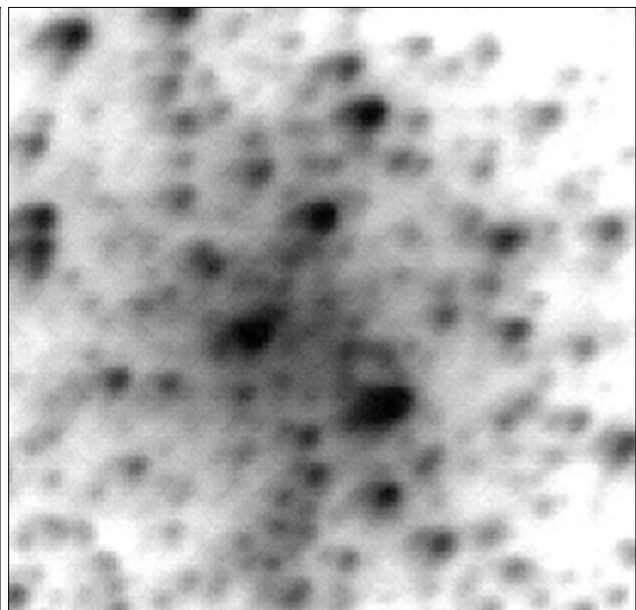
Figure 2. Median C_N^2 profile obtained with the complete sample of 43 nights, the summer [April-June] and winter [October-March] time samples. Results are obtained with the standard GS technique.

Image Degradation by the Atmosphere
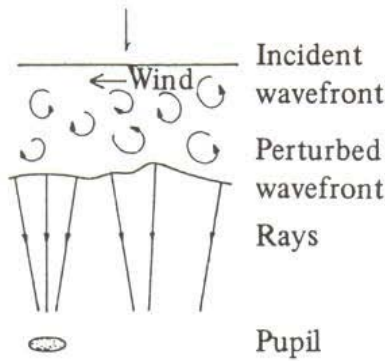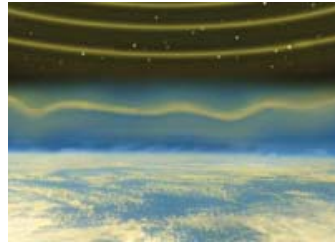## ...and why we care ...!

PHARO LGS Ks image
500s integ., 40" FOV, 150 mas FWHM

WIRO H image
Kobulnicky et al. 2005, AJ 129, 239-250

Aspects of Image Degradation

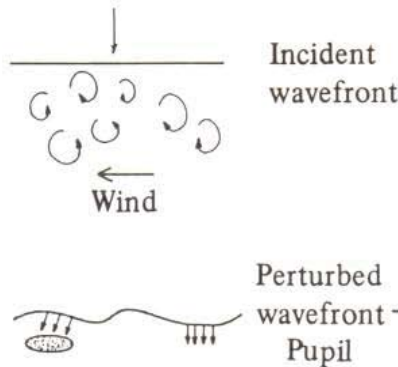**Scintillation** – the energy received by the pupil varies in time

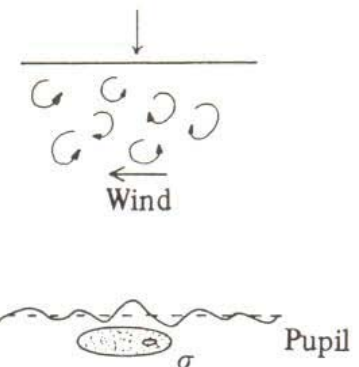**Image motion** – the average slope of the wavefront at the pupil varies ("tip-tilt")

Image blurring – the spatial coherence of the wavefront is reduced ("seeing")

The Fried Parameter r$_0$

The radius of the spatial coherence area is given by the so-called Fried parameter r$_0$:

$$r_0(\lambda) = 0.185\lambda^{6/5}\left[\int_0^\infty C_n^2(z)dz\right]^{-3/5}$$

Note that r$_0$ increases as the 6/5 power of the wavelength and decreases as the -3/5 power of the air mass.

Another "definition" is that r$_0$ is the average turbulent scale over which the RMS optical phase distortion is 1 radian.

The angle $\Delta\theta = \dfrac{\lambda}{r_0}$ is often called the atmospheric seeing.

Short Exposures through Turbulence

Random intensity distribution of speckles in the focal plane:
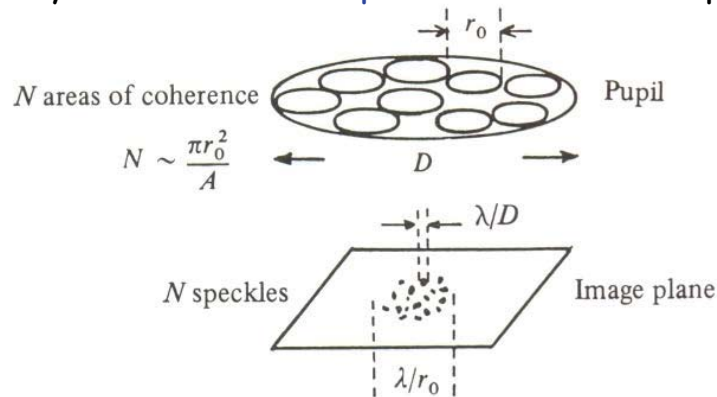
The observed image from some source is given by the convolution of I_0 with the MTF or pupil transfer function $T(\omega)$:

$$I(\theta) = I_0(\theta) * T(\theta) \quad \text{or} \quad \left\langle \left| I(\omega) \right|^2 \right\rangle = \left| I_0(\omega) \right|^2 \left\langle \left| T(\omega) \right|^2 \right\rangle$$

If a point source is observed as reference through the same r_0 we can

calculate: $\quad \left| I_0(\omega) \right| = \left(\dfrac{\left\langle \left| I(\omega) \right|^2 \right\rangle_{obs}}{\left\langle \left| T(\omega) \right|^2 \right\rangle_{obs}} \right)^{1/2} \quad$ This is called speckle interferometry.

Speckle Interferometry

*Example: Real-time bispectrum speckle interferometry: 76 mas resolution.*
http://www.mpifr-bonn.mpg.de/div/ir-interferometry/movie/speckle/specklemovie.html
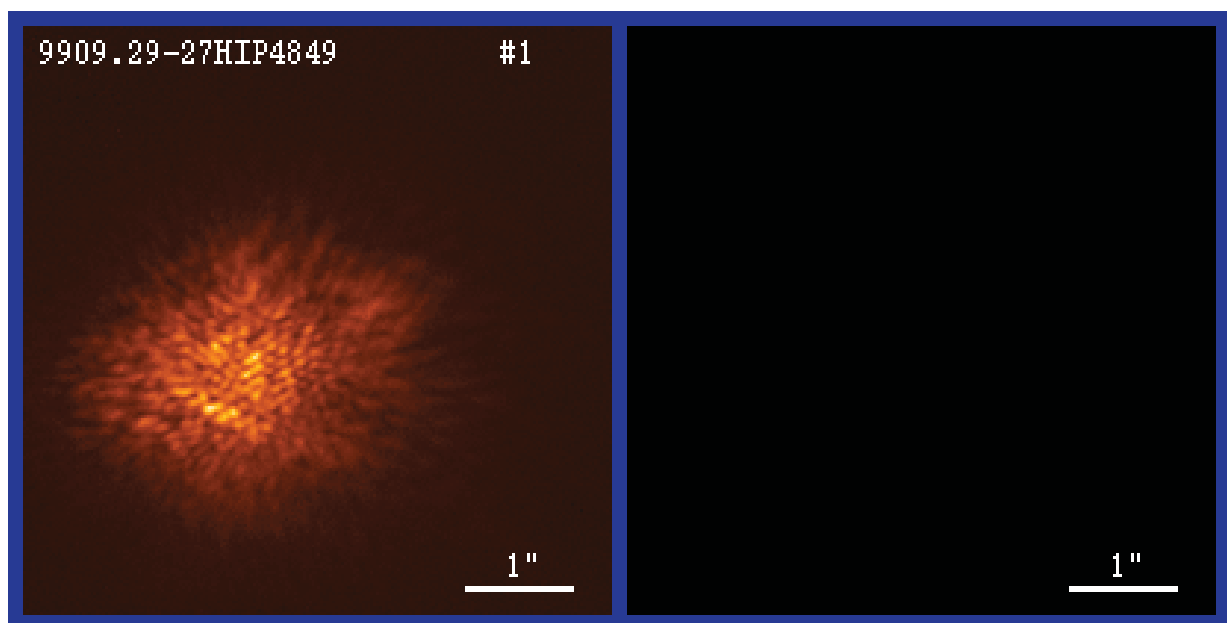
Several related techniques do exist, e.g., Shift-and-add, Lucky Imaging, bispectrum analysis, Aperture masking, Triple correlation, …

Turbulence Correlation Time τ_c

Time series of a patch of atmosphere above the 3.6m telescope aperture (Gendron 1994)
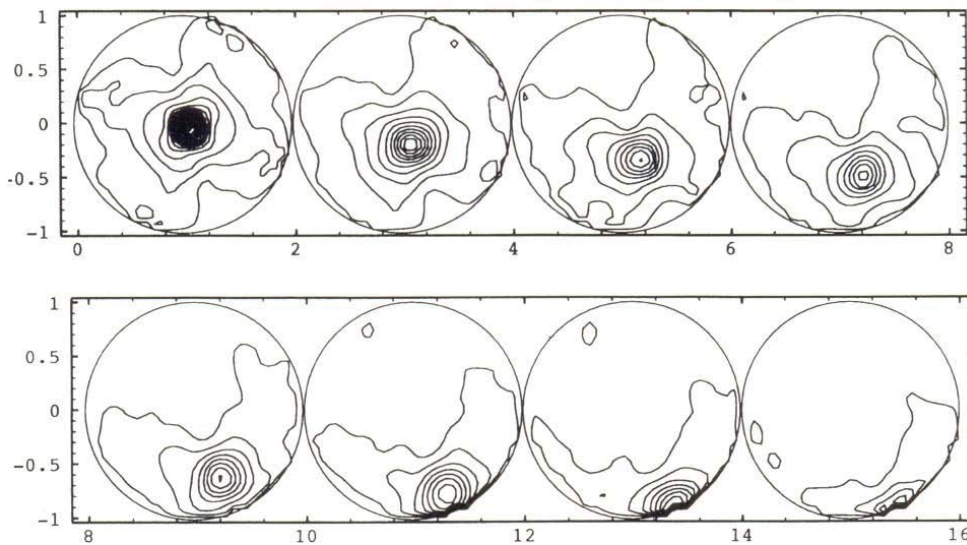
Two effects:
1. The turbulence does not change arbitrarily fast but with a correlation time or coherence time τ_c.
2. Often, the turbulent time scales >> time for the turbulent medium to pass the telescope aperture (wind speed) → "frozen turbulence"

Summary: r_0, seeing, τ_0, θ_0

The Fried parameter $r_0(\lambda) = 0.185\lambda^{6/5}\left[\int_0^\infty C_n^2(z)dz\right]^{-3/5}$ is the radius of the spatial coherence area.
It is the average turbulent scale over which the RMS optical phase distortion is 1 radian. *Note that r_0 increases as $\lambda^{6/5}$.*

$\Delta\theta = \dfrac{\lambda}{r_0} \sim \lambda^{-1/5}$ is called the seeing. At good sites r_0 (0.5μm) ~10 - 30 cm.

The atmospheric coherence (or Greenwood delay) time is: $\tau_0 = 0.314\dfrac{r_0}{\bar{v}}$
It is the maximum time delay for the RMS wavefront error to be less than 1 rad (where v is the mean propagation velocity).

The isoplanatic angle $\theta_0 = 0.314\cos\zeta\dfrac{r_0}{h}$ is the angle over which the RMS wavefront error is smaller than 1 rad.
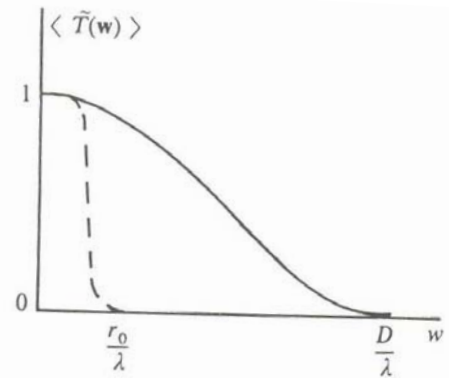
Long Exposures through Turbulence

When $t_{int} \gg \tau_c$ the image is the mean of the instantaneous intensity:

$$I(\theta) = \langle I_0(\theta) * T(\theta, t) \rangle$$

With the mean modulation transfer function (MTF):

$$\left\langle \tilde{T}(\omega) \right\rangle \approx \exp\left[-1.45 k^2 C_n^2 \Delta h \left(\lambda \omega \right)^{5/3} \right]$$

→ The image is smeared or spatially filtered (loss of high spatial frequencies).

The angular dimension now has order of λ/r_0 rather than λ/D.

In other words:
As long as $D > r_0$, bigger telescopes will *not* provide sharper images.