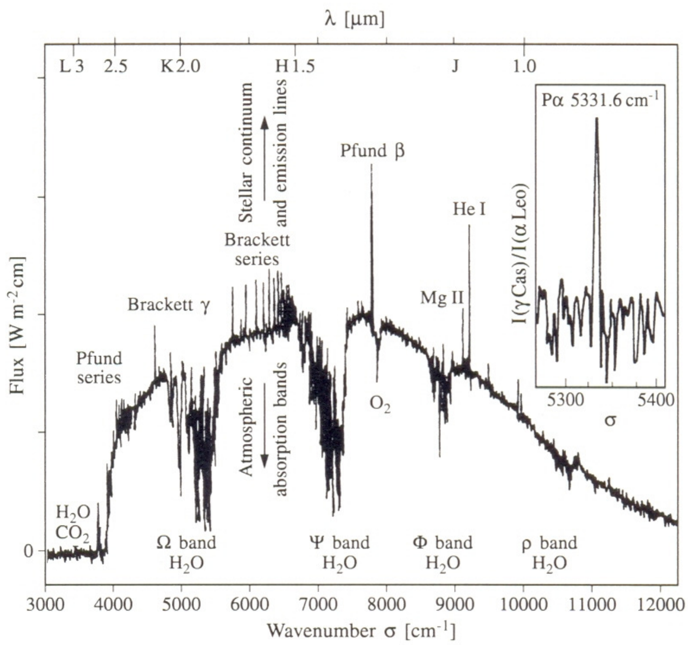
Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

3rd Lecture: 22 September 2010



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.

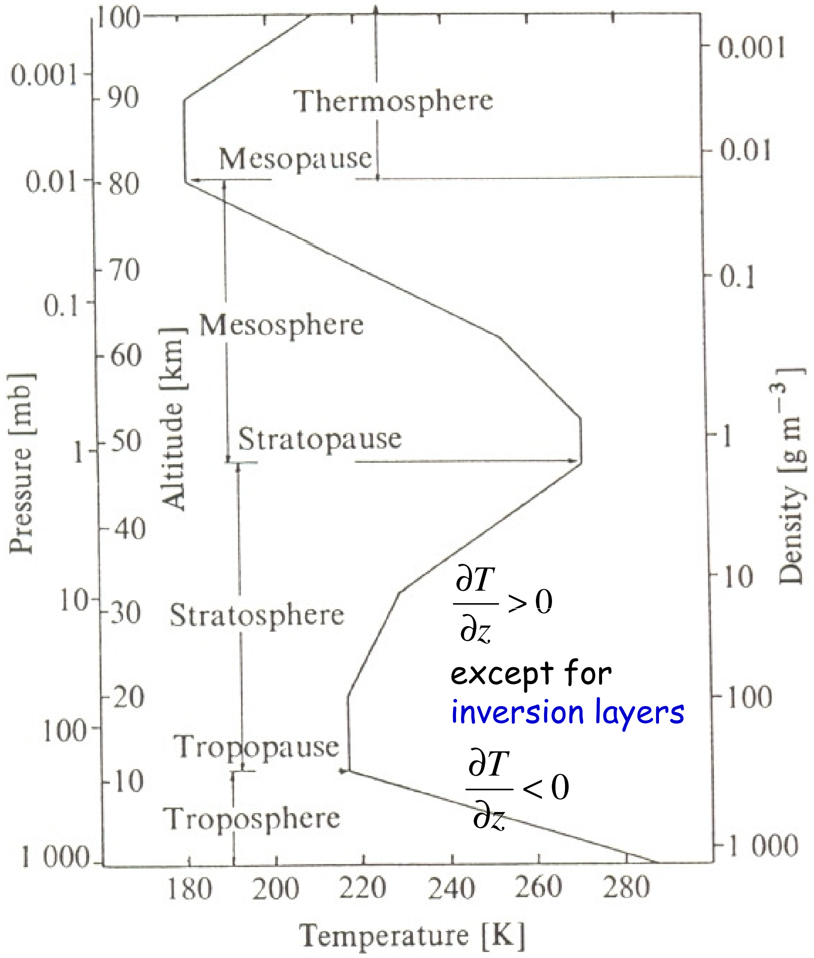
The structure can be described by three parameters:

- altitude z
- temperature T(z)
- density ρ(z)

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

where H = scale height (H ~ 8km near ground).

Vertical Profile

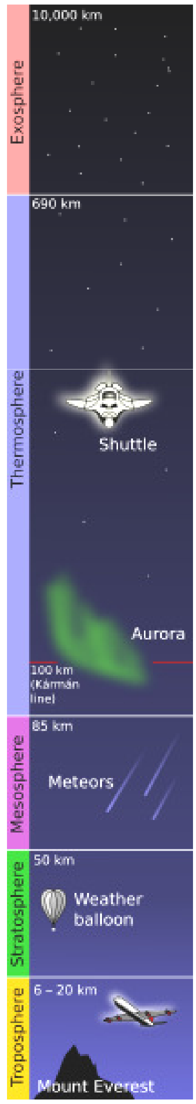


$\frac{\partial T}{\partial z} > 0$

except for inversion layers

$\frac{\partial T}{\partial z} < 0$

Ionosphere



Constituents of the Atmosphere

- Main constituents: O_2 and N_2
  relative constant proportions (78.1% N_2, 20.9% O_2) up to 100 km

- Water vapour – causes very strong absorption bands

- 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)

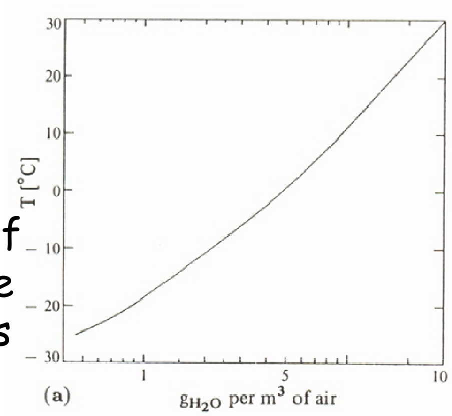
- Ions – varies strongly with altitude and solar activity
  - relevant above 60km where reactions with UV photons occur:

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

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

More on Water Vapor

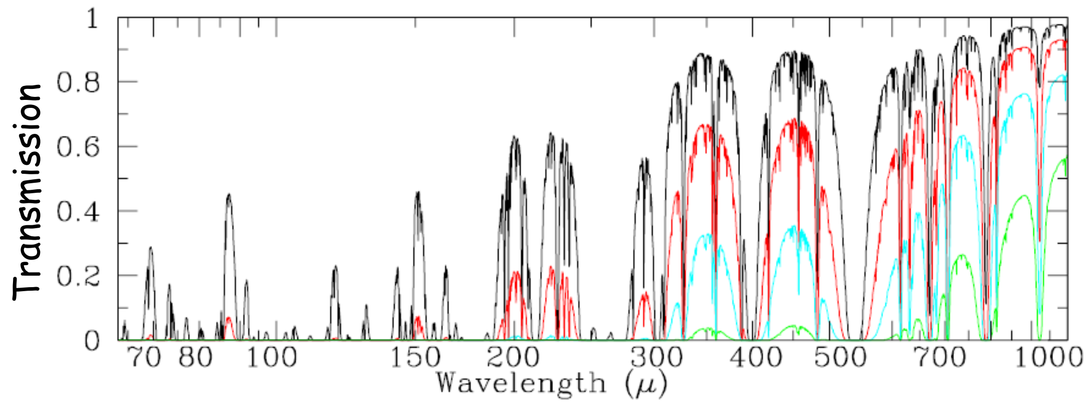
The water vapor is a strong function of *T* and *z*.



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:

$$w(z_0) = \int_{z_0}^{\infty} N_{H_2O} dz , \qquad \text{where} \quad N_{H_2O}[\mathrm{m}^{-3}] = 4.3\times10^{25} \frac{P}{P_0}\frac{T}{T_0} r(z)$$

Scale height for PWV is only ~3 km → observatories on high altitudes



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:

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

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).

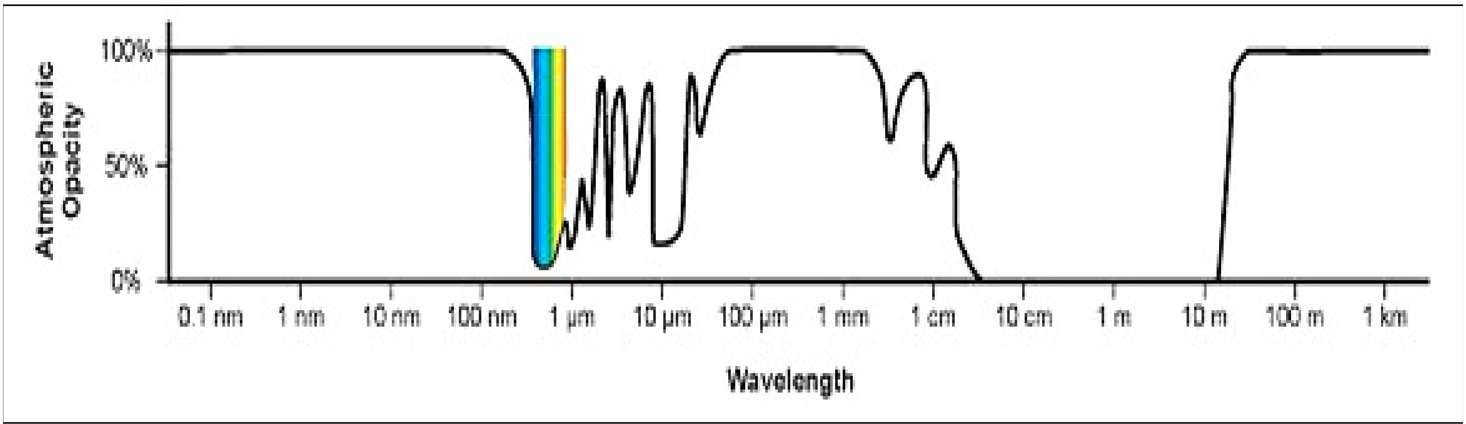
Atmospheric Bands

Two cases of absorption:

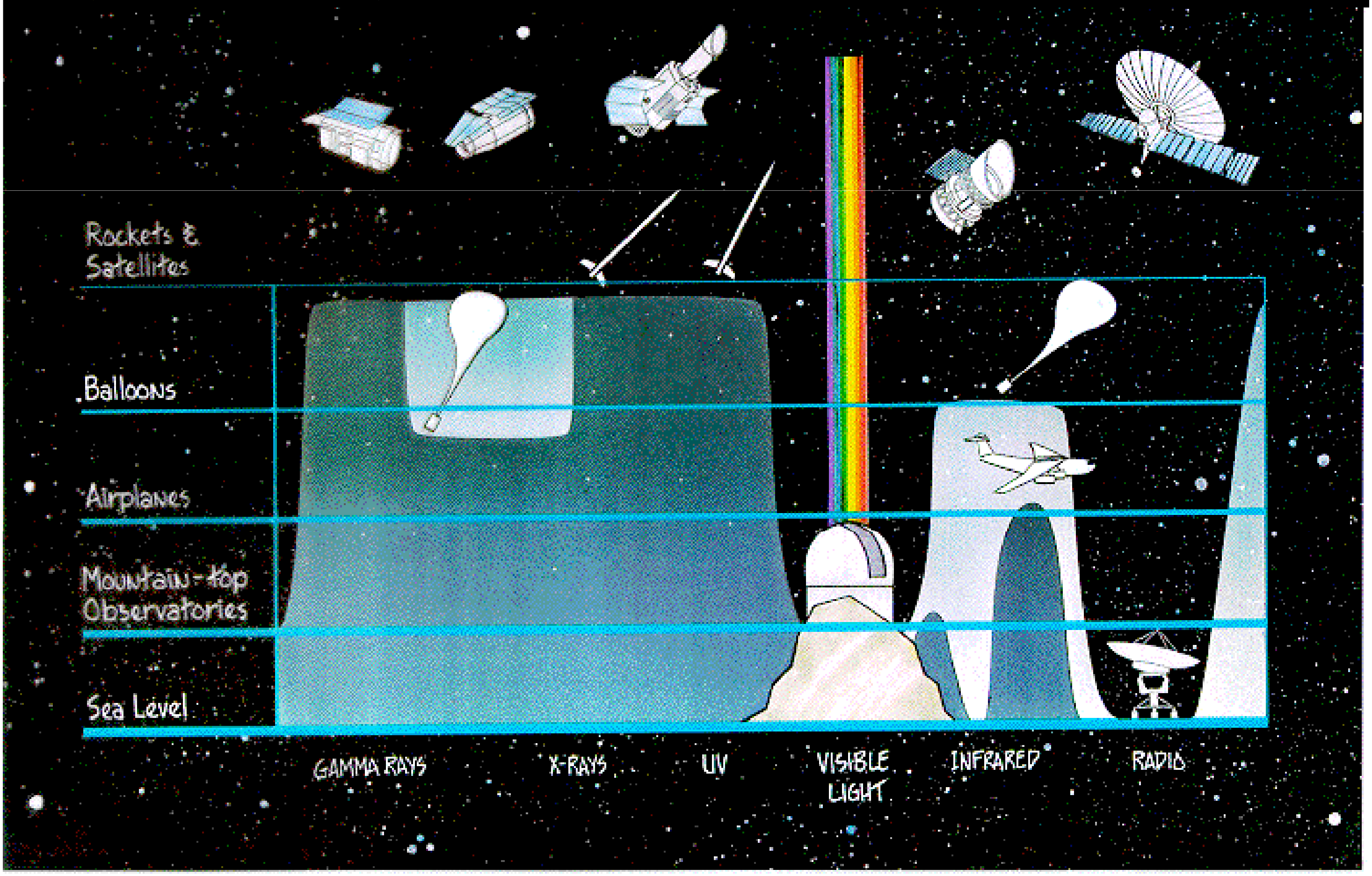
- total absorption → atmospheric transmission windows
- partial absorption → reduced transmission due to narrow telluric* absorption features

**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



Side note: SOFIA

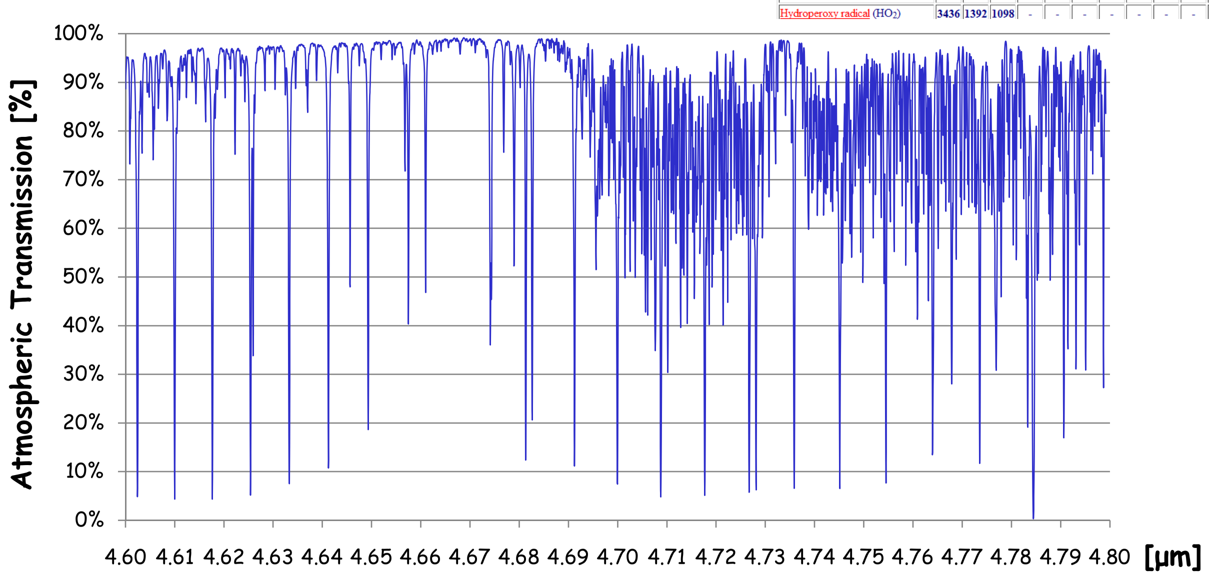
FIR/sub-mm astronomy is also possible from airplanes, e.g. the Stratospheric Observatory for Infrared Astronomy (SOFIA)

Side note: HITRAN

The HITRAN'2004 Database contains 1,734,469 spectral lines for 37 different molecules.

http://cfa-www.harvard.edu/hitran//

Molecule	v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}	v_{11}	v_{12}
Acetylene (C_2H_2)	3374	1974	3289	612	729	-	-	-	-	-	-	-
Ammonia (NH_3)	3337	950	3444	1627	-	-	-	-	-	-	-	-
Carbon dioxide (CO_2)	1388	667	2349	-	-	-	-	-	-	-	-	-
Carbon monoxide (CO)	2143	-	-	-	-	-	-	-	-	-	-	-
Carbon tetrachloride (CCl_4)	464	217	*799*	*316*	-	-	-	-	-	-	-	-
Carbonyl fluoride (COF_2)	1945	963	582	1243	619	774	-	-	-	-	-	-
Carbonyl sulfide (OCS)	859	520	2062	-	-	-	-	-	-	-	-	-
Chlorine nitrate ($ClONO_2$)	1737	1293	809	780	563	435	262	711	120	-	-	-
Chlorine oxide (ClO)	884	-	-	-	-	-	-	-	-	-	-	-
Ethane (C_2H_6)	2954	1388	995	289	2896	1379	2969	1468	823	2985	1469	822
Ethylene (C_2H_4)	3026	1623	1342	1023	3103	1236	949	943	3106	826	2989	1444
Formaldehyde (H_2CO)	2782	1746	1500	2843	1249	1167	-	-	-	-	-	-
Formic acid (HCOOH)	3570	2943	1770	1387	1229	1106	625	1033	638	-	-	-
Hydrogen bromide (HBr)	2559	-	-	-	-	-	-	-	-	-	-	-
Hydrogen chloride (HCl)	2886	-	-	-	-	-	-	-	-	-	-	-
Hydrogen cyanide (HCN)	3311	713	2097	-	-	-	-	-	-	-	-	-
Hydrogen fluoride (HF)	3961	-	-	-	-	-	-	-	-	-	-	-
Hydrogen iodide (HI)	2230	-	-	-	-	-	-	-	-	-	-	-
Hydrogen peroxide (H_2O_2) (τ =1)	3593	1396	866	259	3560	1236	-	-	-	-	-	-
Hydrogen sulfide (H_2S)	2615	1183	2626	-	-	-	-	-	-	-	-	-
Hydroperoxy radical (HO_2)	3436	1392	1098	-	-	-	-	-	-	-	-	-



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:

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

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:

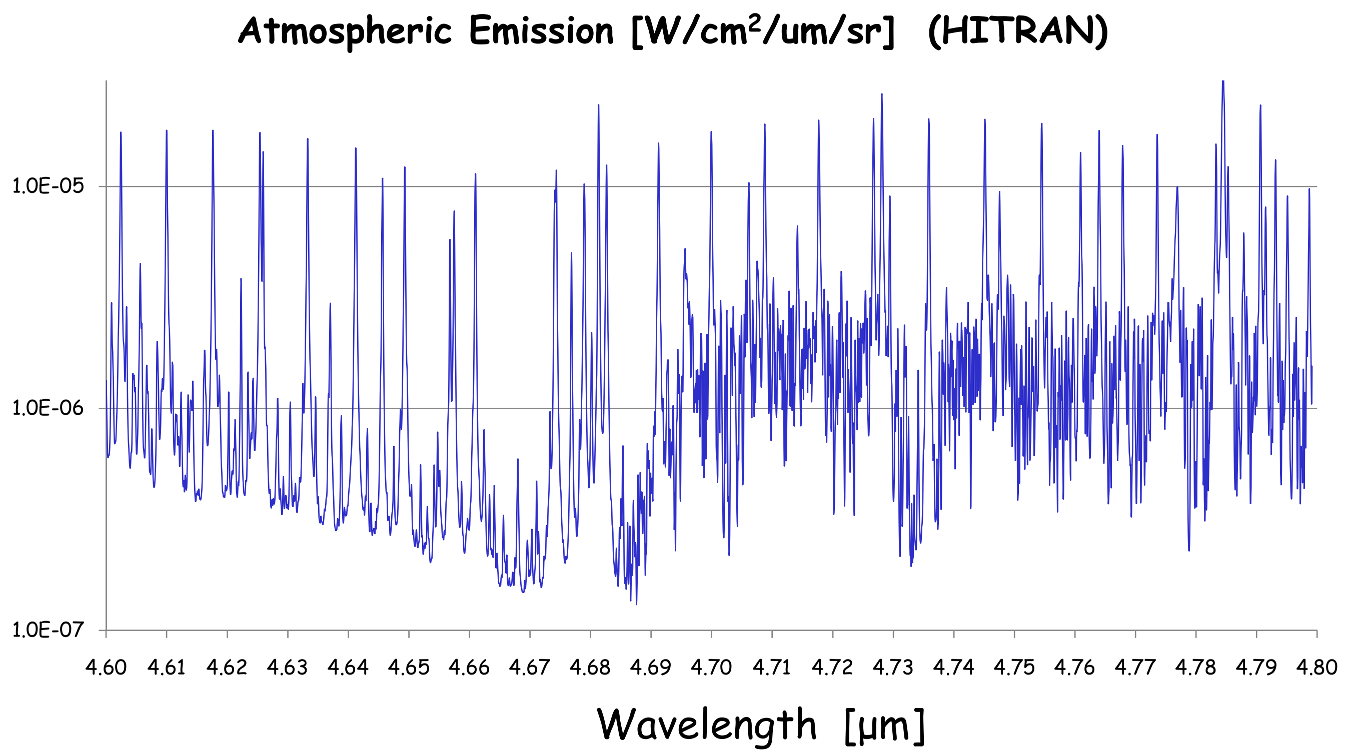
$$I_\lambda(z) = \tau_\lambda B_\lambda(\overline{T})\frac{1}{\cos\theta}$$

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

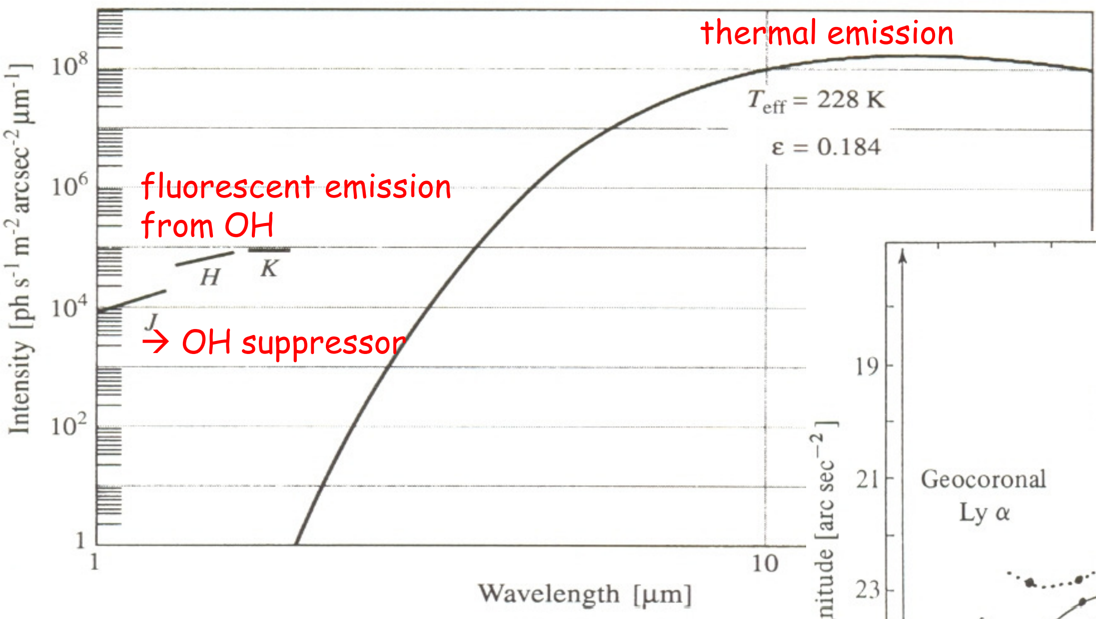
For $\overline{T}$ = 250 K and θ = 0:

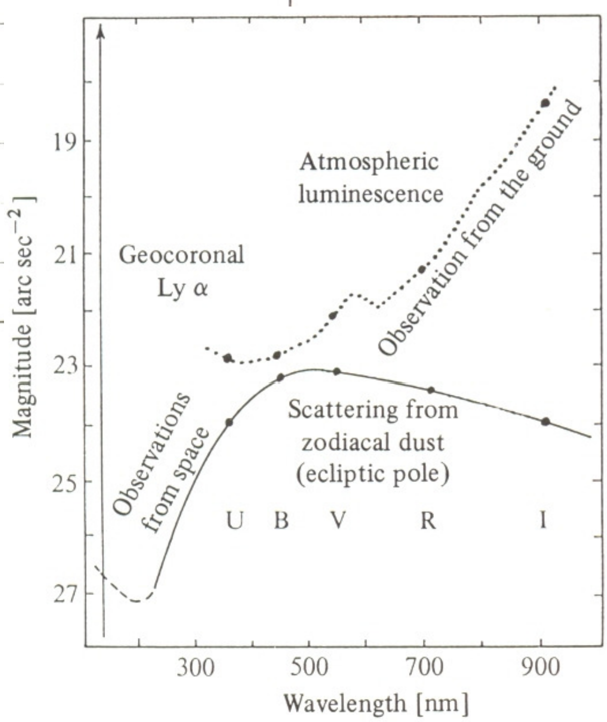
Spectral band (cf. Sect. 3.3)	L	M	N	Q
Mean wavelength [μm]	3.4	5.0	10.2	21.0
Mean optical depth τ	0.15	0.3	0.08	0.3
Magnitude [arcsec^{-2}]	8.1	2.0	−2.1	−5.8
Intensity [Jy arcsec^{-2}][a]	0.16	22.5	250	2 100

Exact Solution: full Radiative Transfer



Fluorescent and Thermal Emission



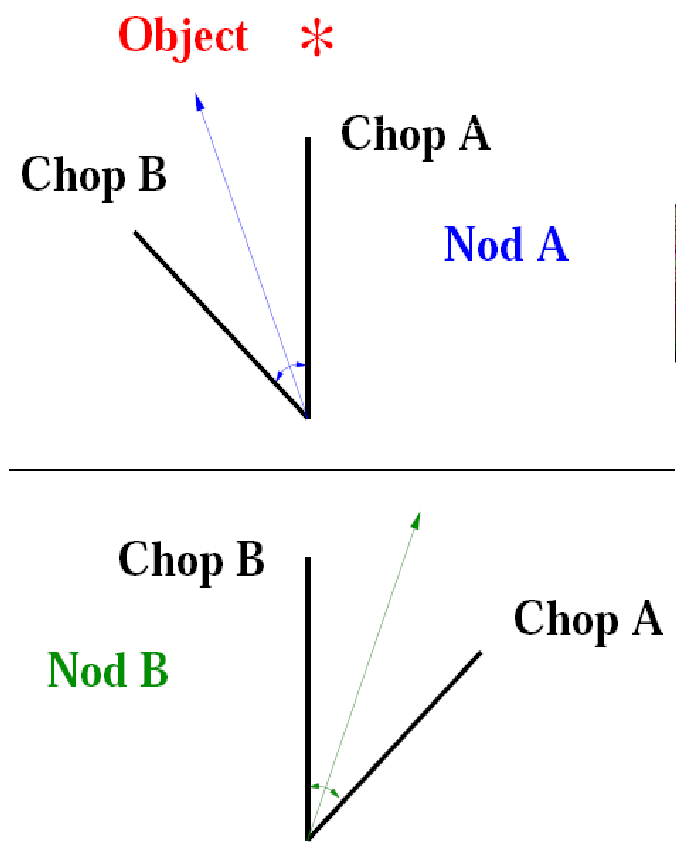


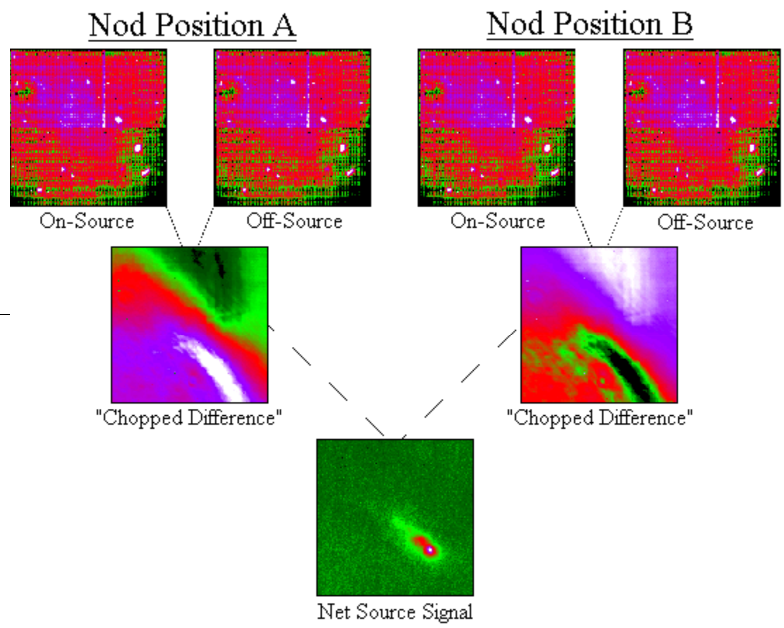
Sky brightness per arcsecond.

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

Chopping & Nodding

High background: Poissonian photon shot noise + spatially & temporally varying fluxes + instrumental drifts/artefacts → chopping/nodding





4. Scattering, Refraction and Dispersion

A. Scattering by Air Molecules

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

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

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

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

B. Aerosol Scattering

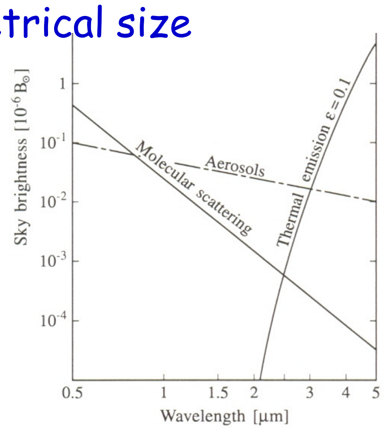
Aerosols (like sea salts, hydrocarbons, volcanic dust) are much bigger than air molecules → Rayleigh scattering does *not* apply.

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 $a \gg \lambda$ 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



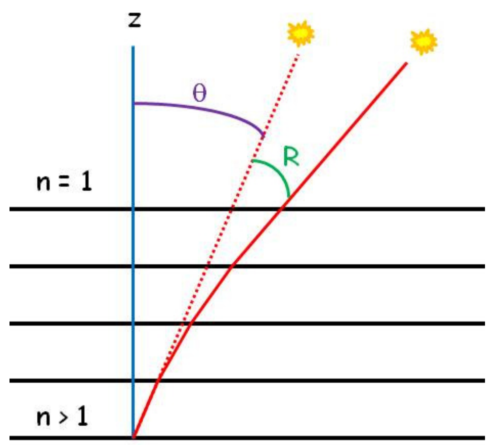
If $a \sim \lambda$ then $Q_s \propto 1/\lambda$ (for dielectric spheres):

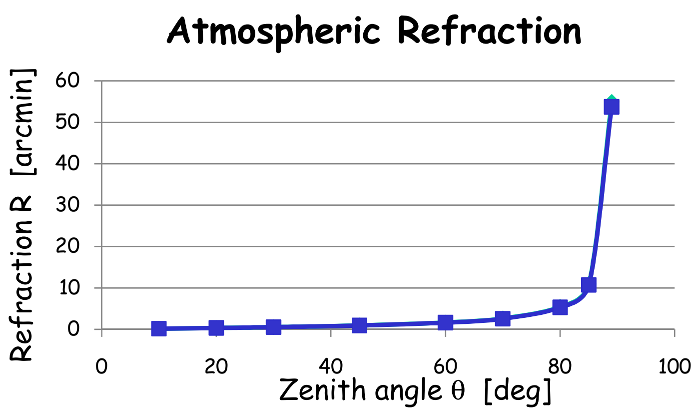
- the scattered intensity goes with $1/\lambda$

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





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

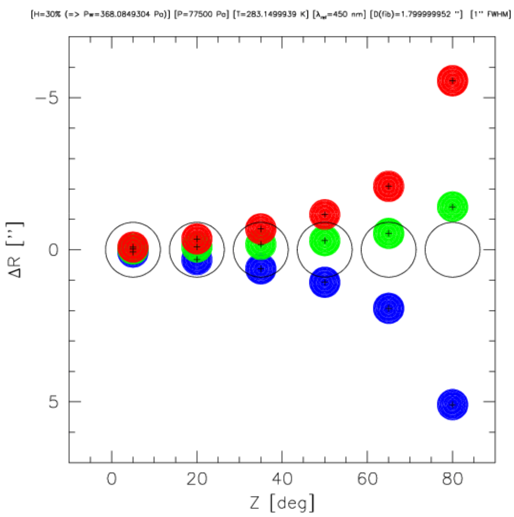
$$[n(\lambda) - 1] \times 10^6 = 64.328 + \frac{29498.1}{146 - \frac{1}{\lambda_0^2}} + \frac{255.4}{41 - \frac{1}{\lambda_0^2}}$$

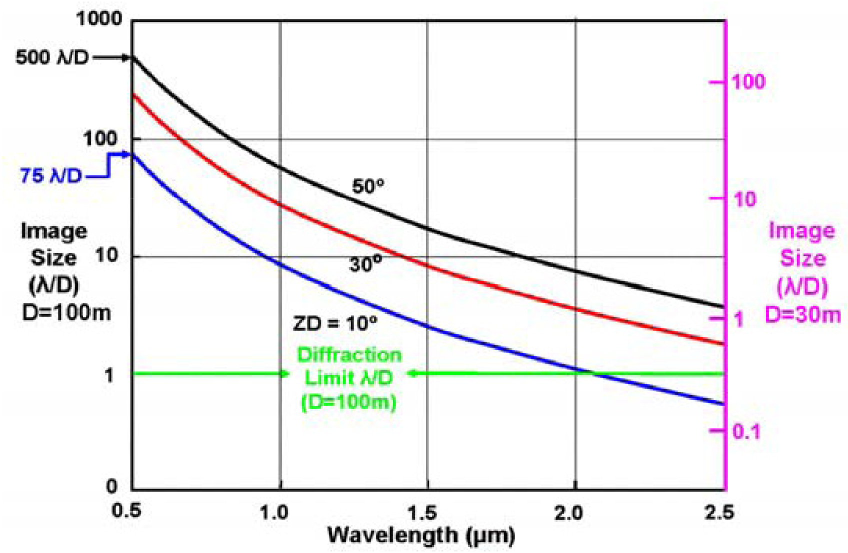
(valid for dry air, 1 atm pressure, T ~ 290K and λ_0 in [μm]).

Atmospheric Dispersion

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

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

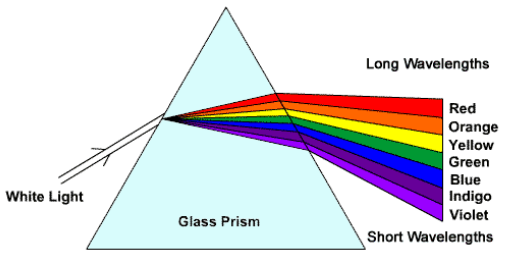


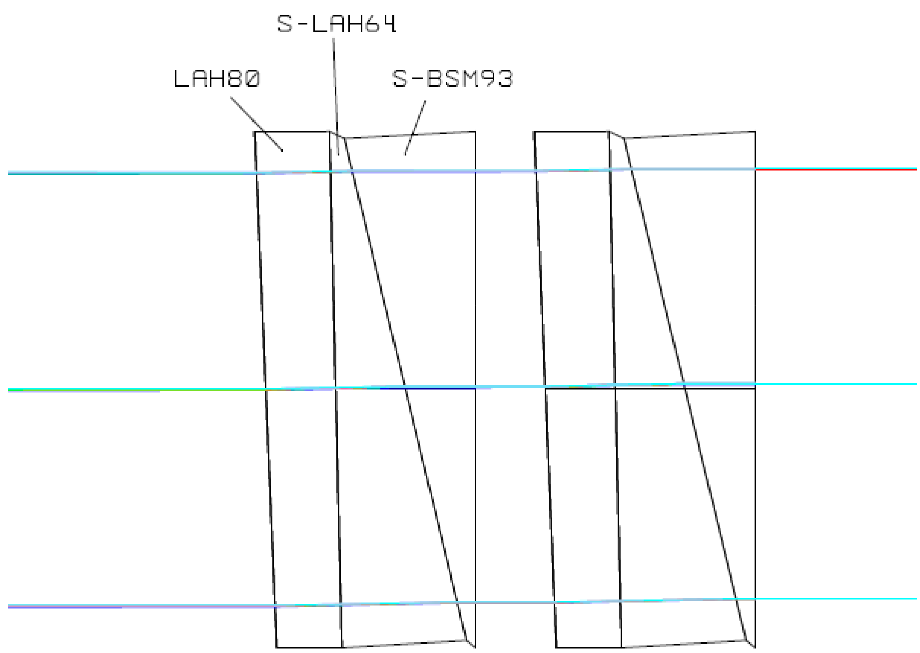


Atmospheric Dispersion Corrector

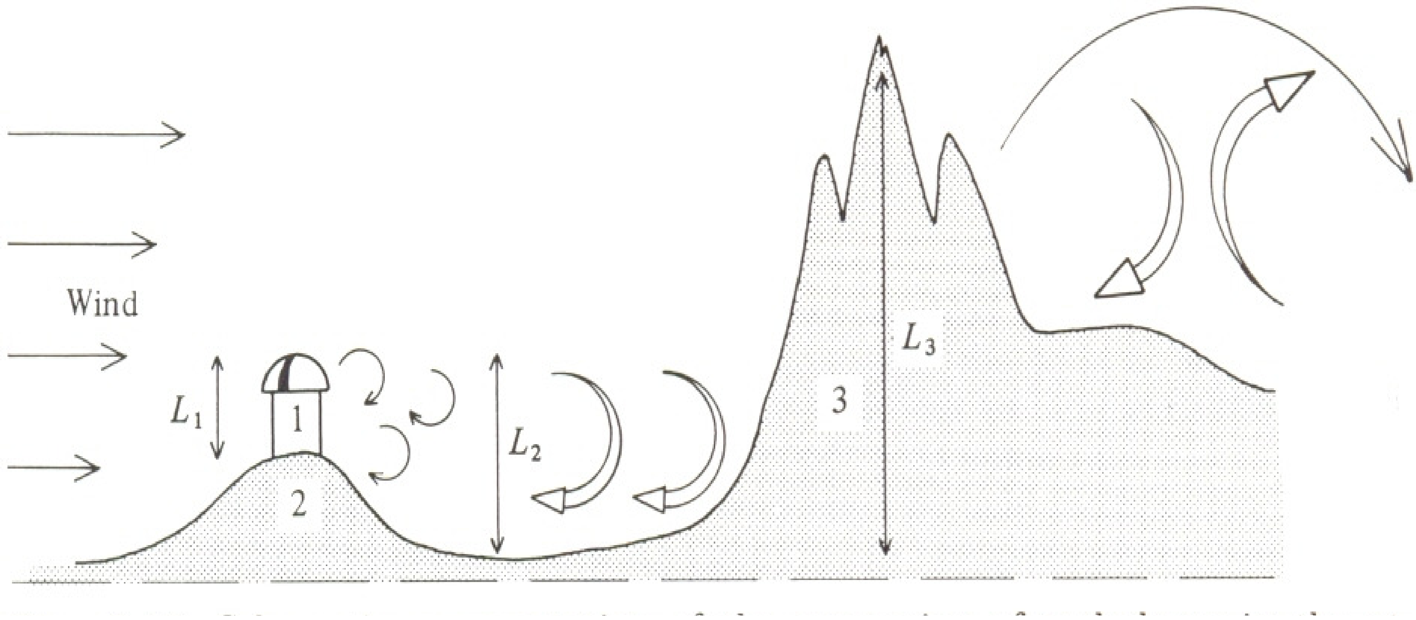
To counterbalance atmospheric dispersion use:

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 happens.

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

The Power Spectrum of Turbulence

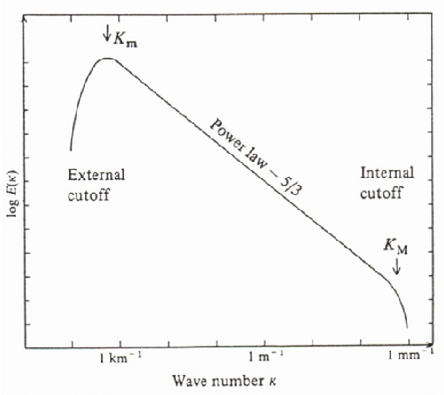
The kinetic energy of large scale (~L) movements is gradually transferred to smaller and smaller scales, down to a minimum scale length l_0, at which the energy is dissipated by viscous friction.

The local velocity field can be decomposed into spatial harmonics of the wave vector $\boldsymbol{\kappa}$.
The reciprocal value $1/\boldsymbol{\kappa}$ 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 $L_0^{-1} < \kappa < l_0^{-1}$



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 $n(r+\rho)$ at a nearby point. The variance of the two values is given by:

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

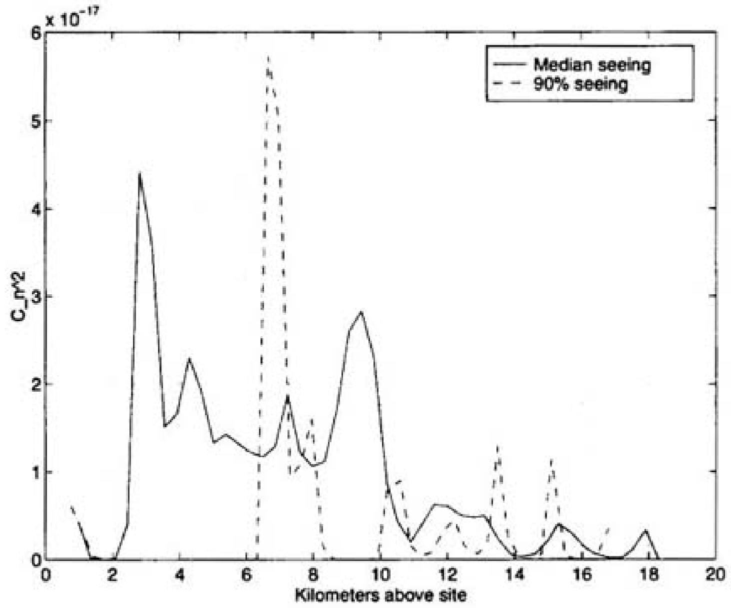
where $D_n(\rho)$ is the index structure function and C_n^2 is the index structure coefficient or structure constant of the refractive index.

Air Refractive Index Fluctuations (2)

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

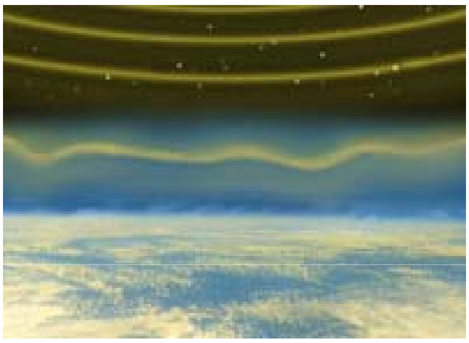
Typical value: $C_n^2 \cdot \Delta h \sim 4 \cdot 10^{-13}$ $cm^{1/3}$ for a 3 km altitude layer

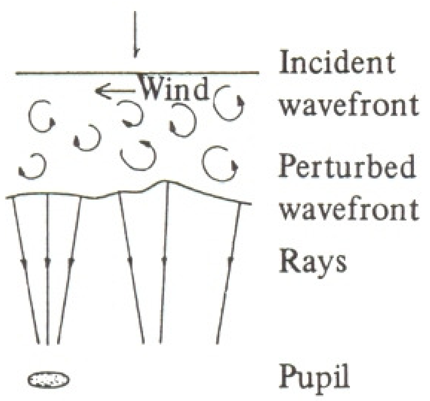
But: there are always several layers of turbulence



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).

Image Degradation by the Atmosphere





Scintillation – the energy received by the pupil varies in time

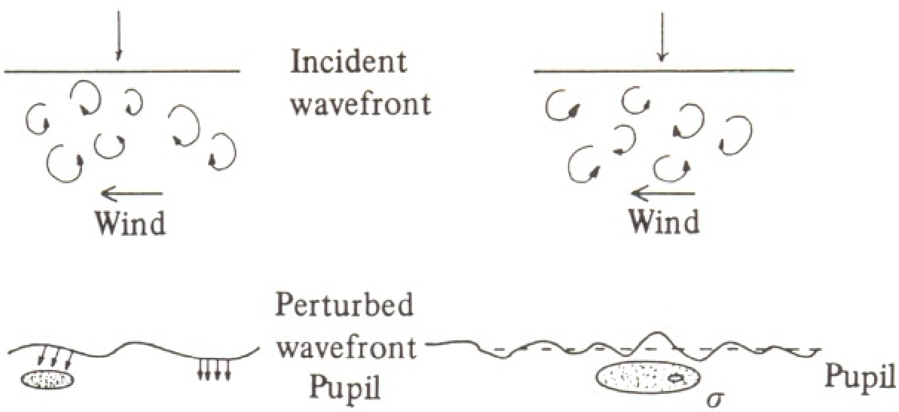
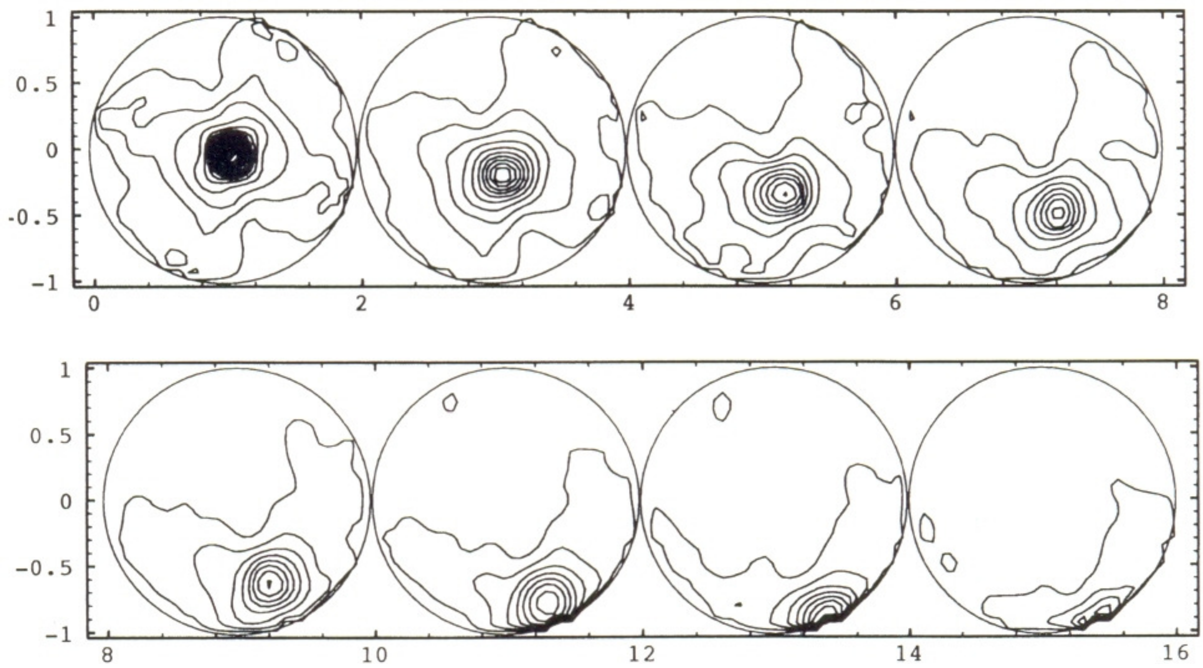


Image motion – the average slope of the wavefront at the pupil varies ("tip-tilt")

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

Turbulence Correlation Time τ_c

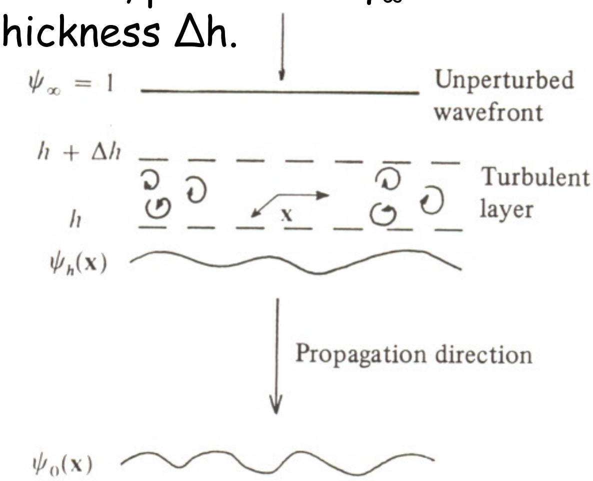
Often: time scales to generate turbulence >> time for the turbulent medium to pass the telescope aperture (← wind speed).
→ correlation time τ_c.



Motion of a "frozen" patch of atmosphere across the 3.6m telescope aperture. Pictures by E. Gendron (1994)

Wavefront Perturbations

Consider a monochromatic, plane wave $\psi_\infty = 1$ which passes through a turbulent layer of thickness Δh.



Then the spatial correlation function of the wave across the telescope aperture is: $\langle \psi_h(x+\xi)\psi_h^*(\xi)\rangle = \exp\left(-1.45k^2 C_n^2 \Delta h\, x^{5/3}\right)$, where $k = 2\pi/\lambda$ and the correlation length x_c is:

$$x_c \approx \left(1.45k^2 C_n^2 \Delta h\right)^{-3/5} = \left(1.45\left(\frac{2\pi}{\lambda}\right)^2 C_n^2 \Delta h\right)^{-3/5} \propto \lambda^{6/5}$$

The Fried Parameter r_0

Related to the correlation length x_c is the so-called Fried parameter r_0. It is the radius of the spatial coherence area:

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

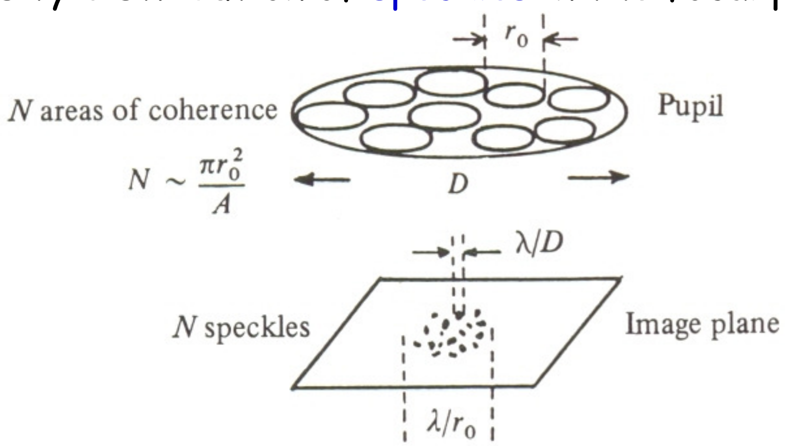
Note that r_0 increases as the 6/5 power of the wavelength and decreases as the -3/5 power of the air mass.

Another "definition" is that r_0 is the average turbulent scale over which the RMS optical phase distortion is 1 radian.

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

Short Exposures through Turbulence

Random intensity distribution of speckles in the focal plane:



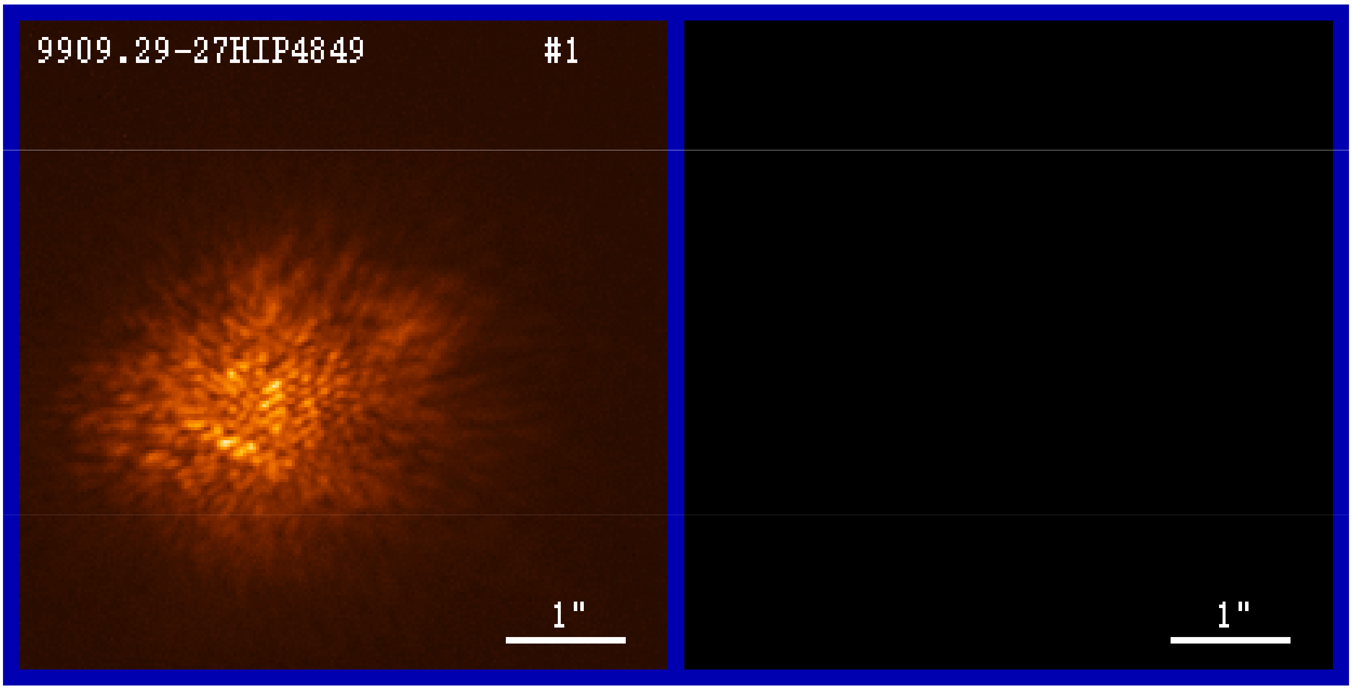
The observed image from some source is given by the convolution of I_0 with the MTF or pupil transfer function $T(\omega)$:

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

If a point source is observed as reference through the same r_0 we can calculate: $|I_0(\omega)| = \left(\frac{\left\langle |I_0(\omega)|^2 \right\rangle_{obs}}{\left\langle |T(\omega)|^2 \right\rangle_{obs}} \right)^{1/2}$ 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, …

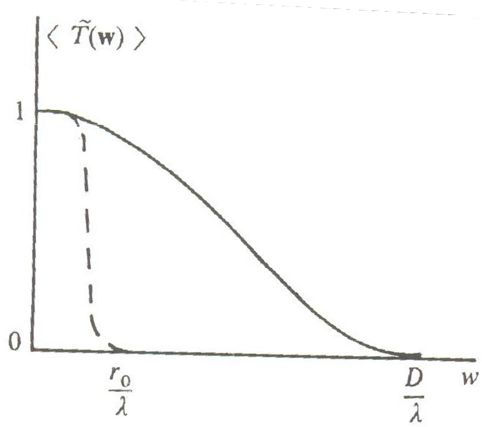
Long Exposures through Turbulence

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):

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



➔ 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.