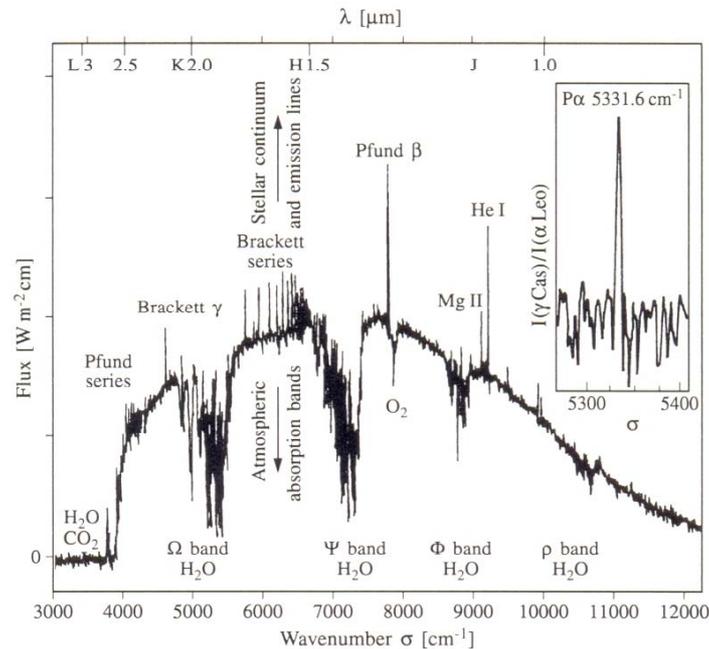


Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

3rd Lecture: 24 September 2008



Based on "Observational Astrophysics" (Springer) by P. Lena, F. Lebrun & F. Mignard, 2nd edition - Chapter 2

We have a full program today:

1. Structure of the Atmosphere
2. Absorption of Radiation
3. Atmospheric Emission
4. Scattering of Radiation
5. Refraction and Dispersion
6. Atmospheric Turbulence (part 1)

1. Structure of the Atmosphere

Vertical Profile

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

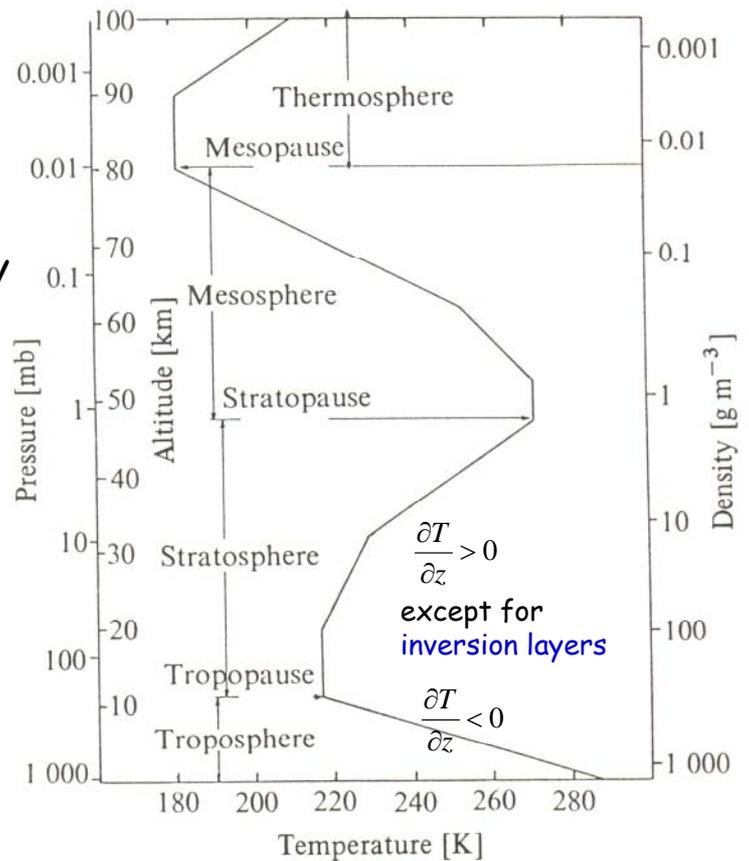
The structure can be described by three parameters:

- altitude z
- temperature $T(z)$
- density $\rho(z)$

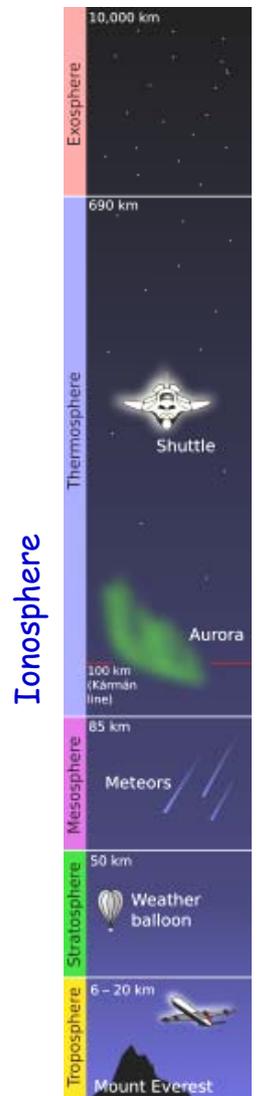
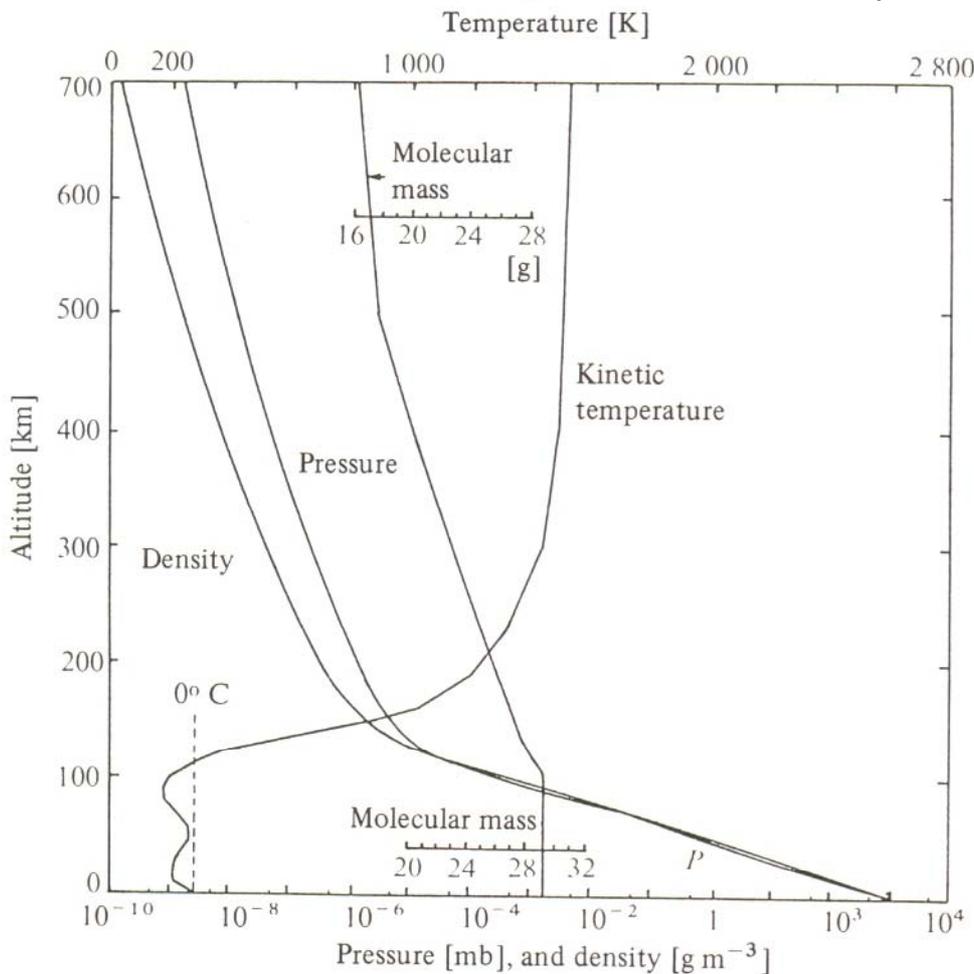
The **pressure $P(z)$** can be described by:

$$P(z) = P_0 e^{-\frac{z}{H}}$$

where **scale height $H \sim 8\text{km}$** near ground.



The higher atmosphere

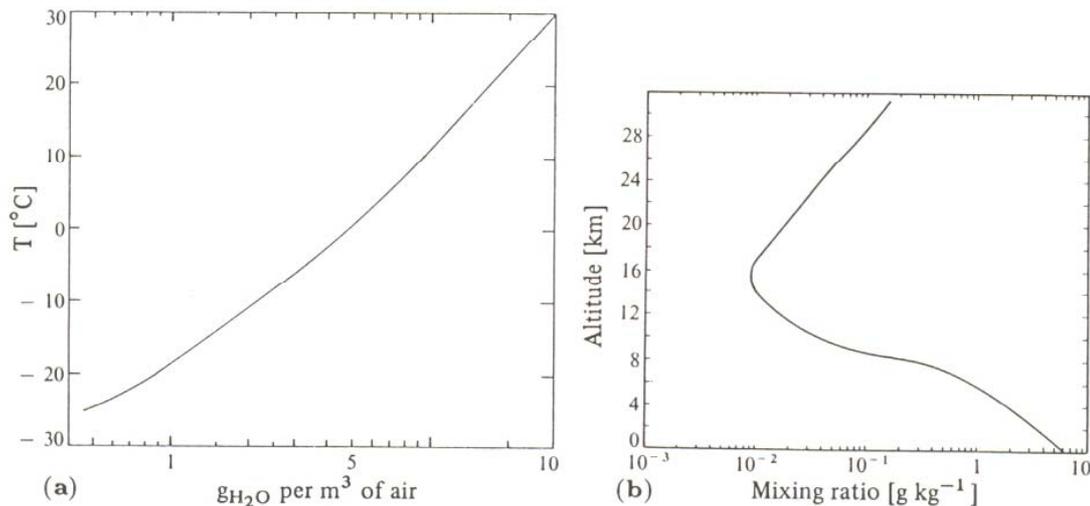


Constituents of the Atmosphere

- 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

the mixing ratio (or content) $r = \frac{\text{mass of } H_2O \text{ per m}^3}{\text{mass of air per m}^3}$ [g/kg]

is a strong function of temperature and altitude.



Side note: Precipitable Water Vapour (PWV)

The amount of PWV above an altitude z is:

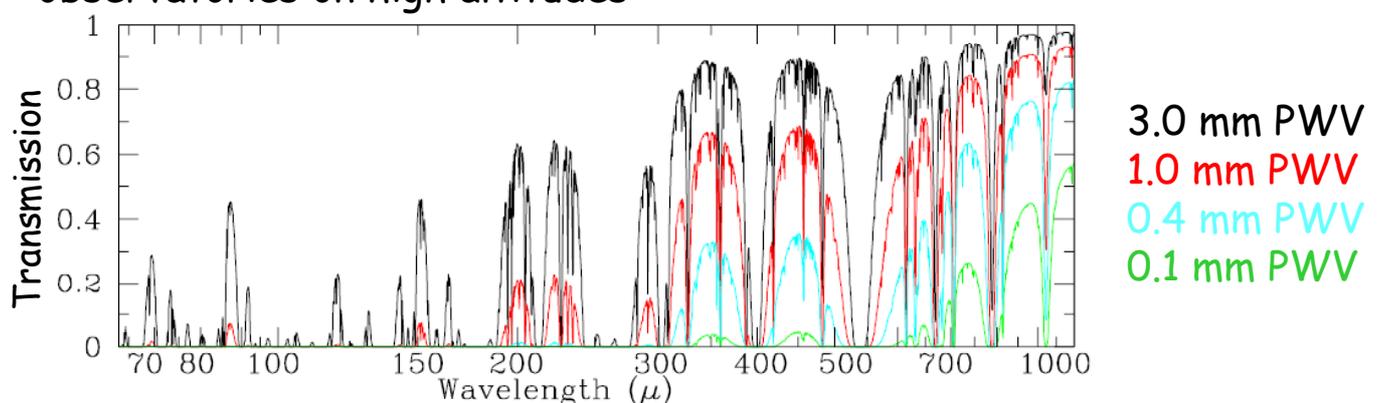
$$w(z_0) = \int_{z_0}^{\infty} N_{H_2O} dz \quad , \text{where}$$

$$N_{H_2O} [m^{-3}] = 4.3 \times 10^{25} \frac{P}{P_0} \frac{T}{T_0} r(z)$$

Normally, PWV is measured and expressed along a column:

$$h_{H_2O} [cm] = \rho_0 [g \text{ cm}^{-3}] \int_{z_0}^{\infty} r(z) e^{-\frac{z}{H}} dz$$

Note that the scale height for PWV is much less ~ 3 km only \rightarrow observatories on high altitudes



Constituents of the Atmosphere (2)

Other constituents:

- **Ozone**

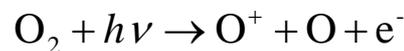
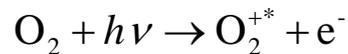
- distribution depends on latitude and season
- maximum concentration around 16 km height
- mainly UV absorption

- **CO₂**

- important component for (mid)IR absorption
- mixing independent of altitude (similar to N₂, O₂)

- **Ions**

- relevant above 60km where reactions with UV photons occur:



- varies with altitude and solar activity
- electron showers along magnetic fields cause Aurora
- at 100 - 300 km height: $n_e \sim 10^5 - 10^6 \text{ cm}^{-3}$

2. Absorption of Radiation

Two cases of absorption:

total absorption → atmospheric **transmission windows**

partial absorption → reduced transmission due to **telluric absorption bands**

Telluric = related to the Earth; of terrestrial origin

Problem: distinguish the telluric lines from intrinsic spectral features of the source.

Atomic and molecular transitions that cause absorption features:

- **pure rotational** molecular transitions: H₂O, CO₂, O₃,
- **rotation-vibrational** molecular transitions: CO₂, NO, CO
- **electronic** molecular transitions: CH₄, CO, H₂O, O₂, O₃, OH
- **electronic** atomic transitions: O, N, ...

Attenuation

The **attenuation** at altitude z_0 is given by:

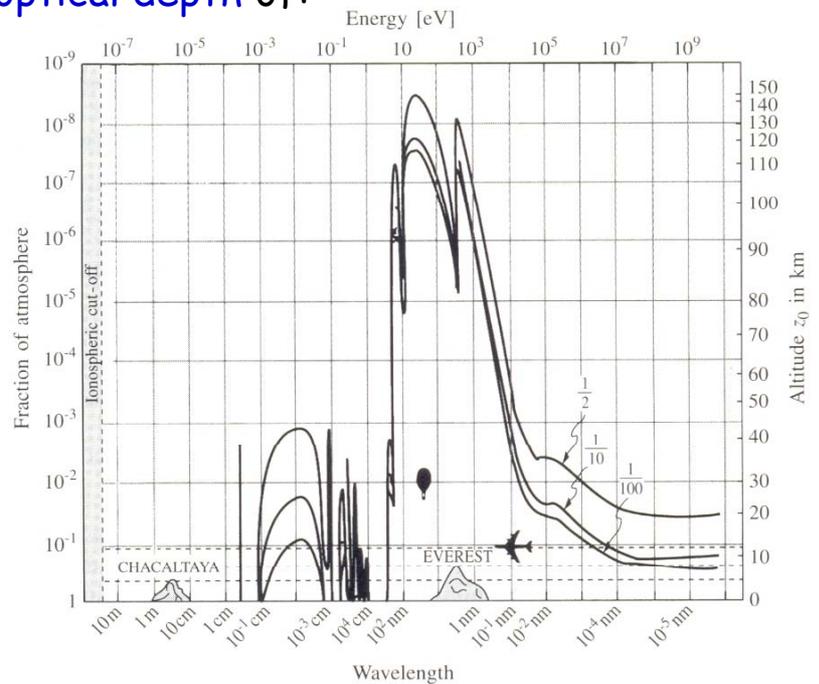
$$\frac{I(z_0)}{I_0} = \exp\left[-\frac{1}{\cos\theta} \sum_i \tau_i(\lambda, z_0)\right]$$

for i absorbing species with an **optical depth** of:

$$\tau_i(\lambda, z_0) = \int_{z_0}^{\infty} r_i(z) \rho_0(z) \kappa_i(\lambda) dz$$

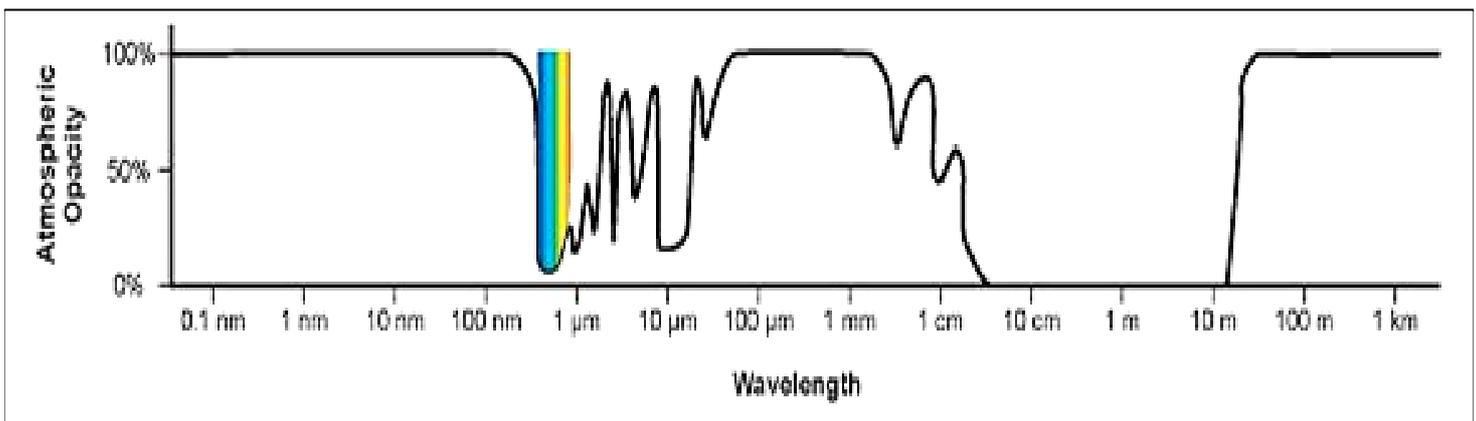
(κ is the absorption coefficient)

Right: Attenuation of electromagnetic radiation as a function of wavelength for three values of $I(z_0)/I_0 = 1/2, 1/10,$ and $1/100$.



Atmospheric Bands (simplified)

(Total) atmospheric absorption defines the **atmospheric bands**.



→ **Ground based astronomy** is limited to visible, near/mid-IR and radio wavelengths.

Space astronomy can also cover γ -rays, X-rays, UV, FIR, sub-mm

(Total) atmospheric absorption defines the atmospheric bands.

...not quite: sub-mm astronomy is also possible from very altitudes and airplanes (KAO, SOFIA) and X-ray and γ -ray from balloons (30-40km).

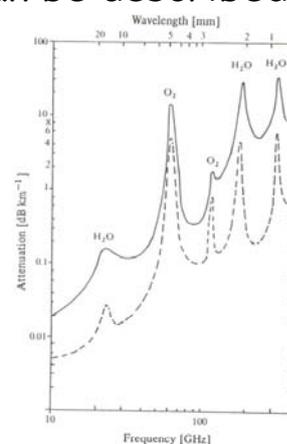
Side note: Spectral Line Profiles

Spectral lines have a finite width due the intrinsic width of the energy levels, leading to **natural line broadening**.

A line for which the shape is dominated by **pressure broadening** (collisions) has a **Lorentz profile** or **damping profile**, and can be described by:

$$\phi(\nu, \nu_0) = \frac{\frac{\Delta\nu_L}{2\pi}}{(\nu - \nu_0)^2 + \left(\frac{\Delta\nu_L}{2}\right)^2}$$

where ν_0 is the central frequency, and $\Delta\nu_L$ is the width.



Other broadening mechanisms are **Doppler broadening** (thermal), **turbulent broadening** and **instrumental profiles** (unresolved lines), which can be best described by a **Gaussian profile**.

HITRAN

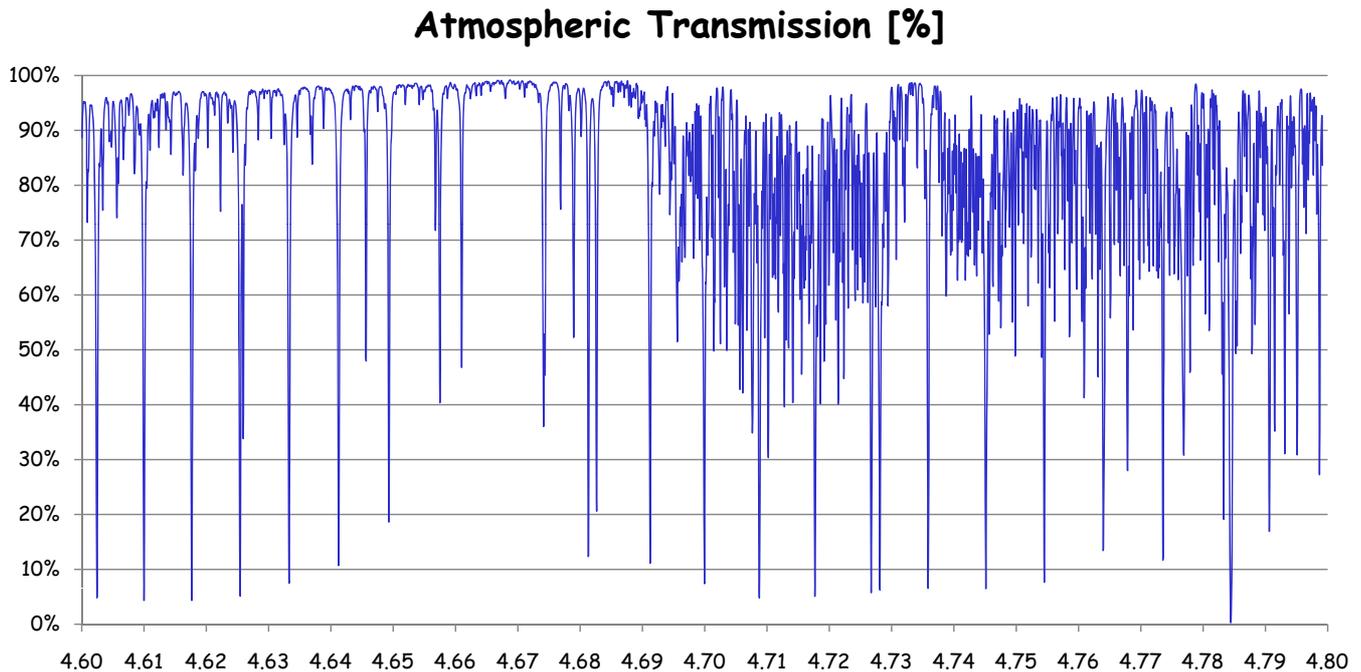
The HITRAN'2004 Database contains 1,734,469 spectral lines for 37 different molecules, e.g.,



Molecule	ν_1	ν_2	ν_3	ν_4	ν_5	ν_6	ν_7	ν_8	ν_9	ν_{10}	ν_{11}	ν_{12}
<u>Acetylene</u> (C ₂ H ₂)	3374	1974	3289	612	729	-	-	-	-	-	-	-
<u>Ammonia</u> (NH ₃)	3337	950	3444	1627	-	-	-	-	-	-	-	-
<u>Carbon dioxide</u> (CO ₂)	1388	667	2349	-	-	-	-	-	-	-	-	-
<u>Carbon monoxide</u> (CO)	2143	-	-	-	-	-	-	-	-	-	-	-
<u>Carbon tetrachloride</u> (CCl ₄)	464	217	799	316	-	-	-	-	-	-	-	-
<u>Carbonyl fluoride</u> (COF ₂)	1945	963	582	1243	619	774	-	-	-	-	-	-
<u>Carbonyl sulfide</u> (OCS)	859	520	2062	-	-	-	-	-	-	-	-	-
<u>Chlorine nitrate</u> (ClONO ₂)	1737	1293	809	780	563	435	262	711	120	-	-	-
<u>Chlorine oxide</u> (ClO)	884	-	-	-	-	-	-	-	-	-	-	-
<u>Ethane</u> (C ₂ H ₆)	2954	1388	995	289	2896	1379	2969	1468	823	2985	1469	822
<u>Ethylene</u> (C ₂ H ₄)	3026	1623	1342	1023	3103	1236	949	943	3106	826	2989	1444
<u>Formaldehyde</u> (H ₂ CO)	2782	1746	1500	2843	1249	1167	-	-	-	-	-	-
<u>Formic acid</u> (HCOOH)	3570	2943	1770	1387	1229	1106	625	1033	638	-	-	-
<u>Hydrogen bromide</u> (HBr)	2559	-	-	-	-	-	-	-	-	-	-	-
<u>Hydrogen chloride</u> (HCl)	2886	-	-	-	-	-	-	-	-	-	-	-
<u>Hydrogen cyanide</u> (HCN)	3311	713	2097	-	-	-	-	-	-	-	-	-
<u>Hydrogen fluoride</u> (HF)	3961	-	-	-	-	-	-	-	-	-	-	-
<u>Hydrogen iodide</u> (HI)	2230	-	-	-	-	-	-	-	-	-	-	-
<u>Hydrogen peroxide</u> (H ₂ O ₂) ($\tau = 1$)	3593	1396	866	259	3560	1236	-	-	-	-	-	-
<u>Hydrogen sulfide</u> (H ₂ S)	2615	1183	2626	-	-	-	-	-	-	-	-	-
<u>Hydroperoxy radical</u> (HO ₂)	3436	1392	1098	-	-	-	-	-	-	-	-	-

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

HITRAN: Transmission



3. Atmospheric Emission

Atmospheric emission = fluorescence & thermal

A. Fluorescent Emission

Fluorescence = recombination of electrons with ions (recombination probability is low, often 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, O₂, OH (←NIR), H

The emission intensity is measured in **Rayleigh**:

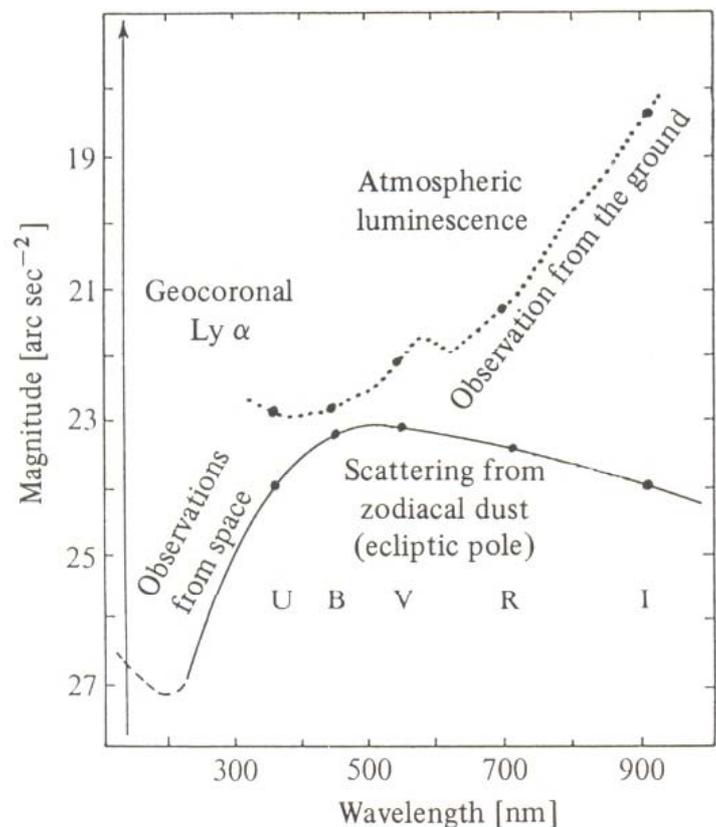
$$1 \text{ Rayleigh} = 10^6 \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} = \frac{1.58 \cdot 10^{-11}}{\lambda[\text{nm}]} \text{ W cm}^{-2} \text{ sr}^{-1}$$

"The Sky is the Limit ..."

Central question: When does the optical/NIR sky become brighter than the stars?

Important: sky brightness per arcsecond.

Remember: even an unresolved point source has a finite angular diameter when viewed through a telescope.



Thermal Emission of the Atmosphere

Up to 60 km is the atmosphere in **local thermodynamic equilibrium** (LTE), thermally populating excitation levels.

Calculating the specific energy received requires a **full radiative transfer calculation** (see next slide).

For $\tau \ll 1$ one can use the approximation

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

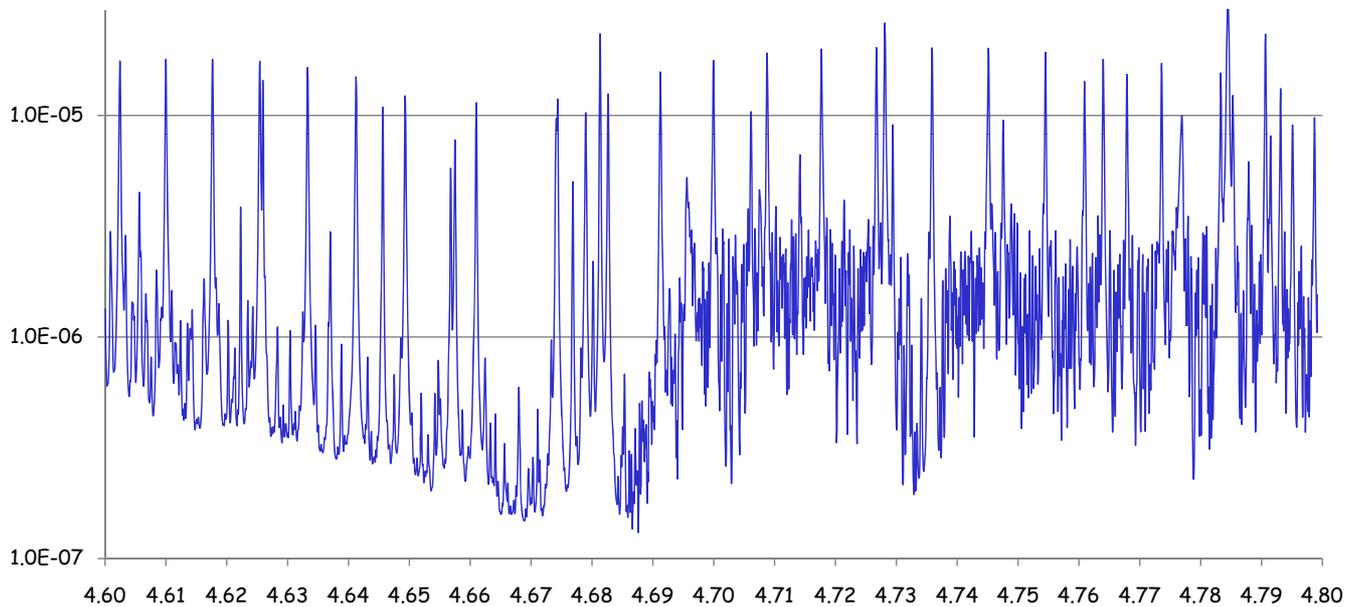
where $B(T)$ is the Planck function at the mean temperature T of the atmosphere.

This is most relevant for the:

- thermal-infrared window: 2 - 30 μm
- millimeter window: 500nm - 2 mm

HITRAN + radiation transfer: Emission

Atmospheric Emission [$\text{W}/\text{cm}^2/\mu\text{m}/\text{sr}$]



Mean Thermal Emission

In the zenith direction and $T = 250 \text{ K}$ (mean temperature) one calculates:

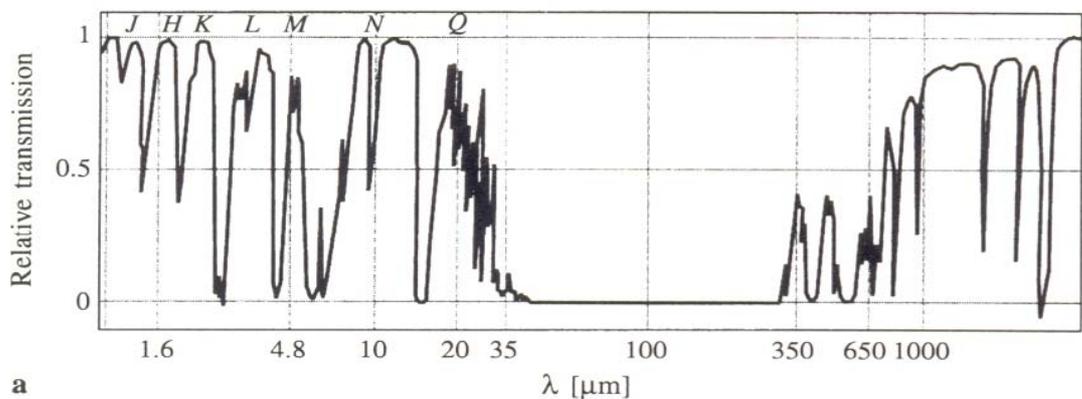
Table 2.3. Mean thermal emission of the atmosphere

Spectral band (cf. Sect. 3.3)	<i>L</i>	<i>M</i>	<i>N</i>	<i>Q</i>
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	2100

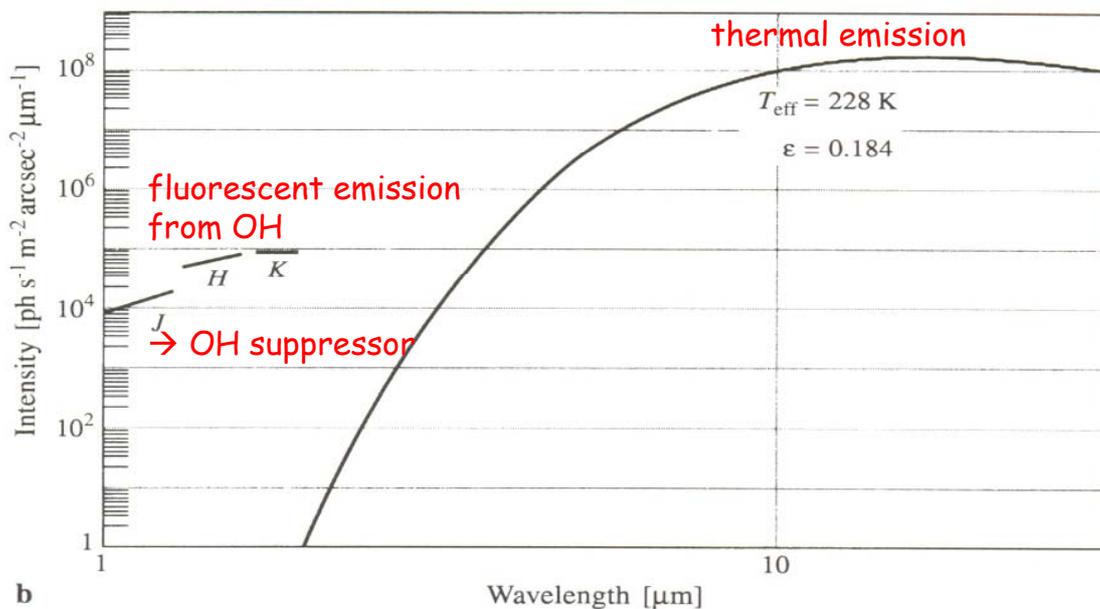
^a 1 Jansky = $10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$.

Note that objects can be much fainter than the sky brightness
→ subtraction techniques, e.g. "sky chopping"

Fluorescent and Thermal Emission



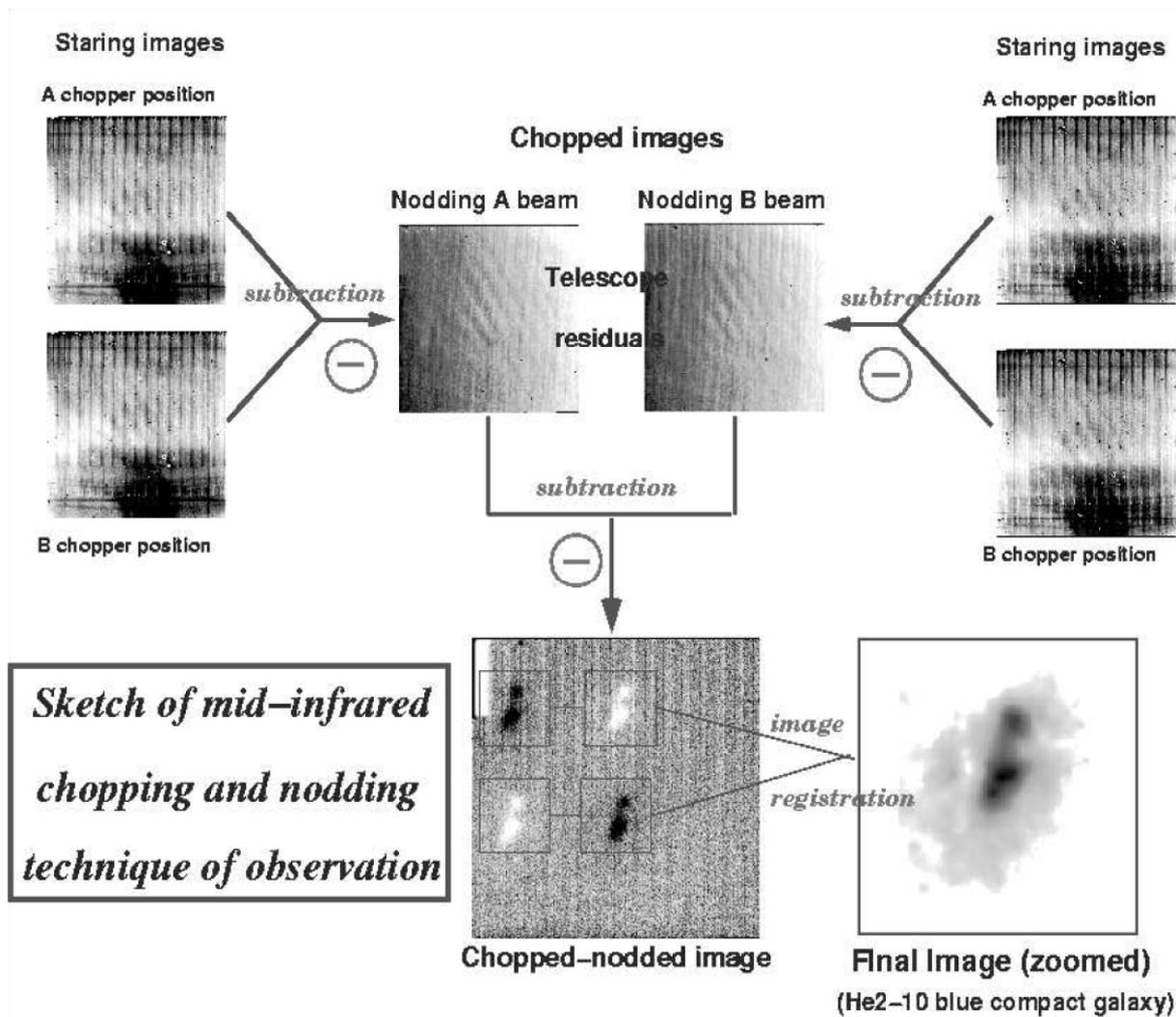
a



b

“Sky Chopping”

Usually done with the telescope secondary mirror at ~ 1 Hz.



4. Scattering of Radiation

Atmospheric scattering = air molecules & aerosols

Molecular Scattering

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 ($n-1 \sim 8 \cdot 10^{-5} P/T$).

Remember, Rayleigh scattering is not isotropic:

$$I_{scattered} = I_0 \frac{3}{16\pi} \sigma_R (1 + \cos^2 \theta) d\omega$$

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):

$$\sigma_M = \pi a^2 (Q_{scattering} + Q_{absorption})$$

If $a \gg \lambda$ then $Q_s = Q_a = 1$ and hence:

- the scattered power is equal to the absorbed power
- the effective cross section is twice the geometrical size

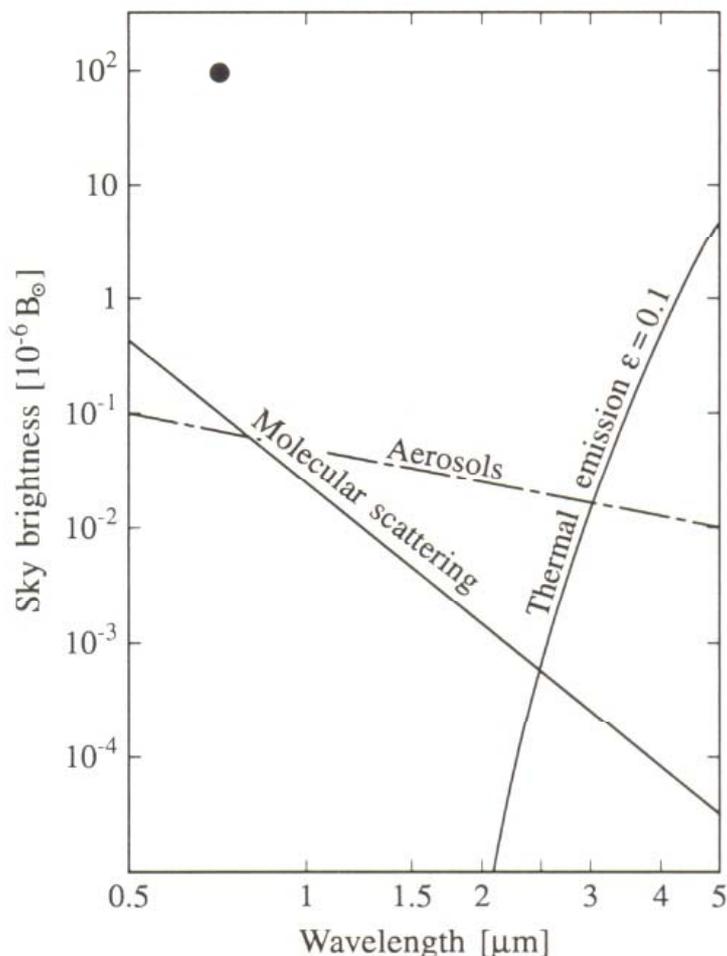
If $a > \lambda$ then $Q_s \propto 1/\lambda$ (for dielectric spheres) and hence:

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

Day and Night-time Observations

From the sky brightness point of view some observations will be possible during day time, depending on what the limiting component is.

However, other considerations (heat load from the Sun, turbulence, etc.) may apply.



5. Refraction and Dispersion

The refractive index of air strongly depends on the wavelength:

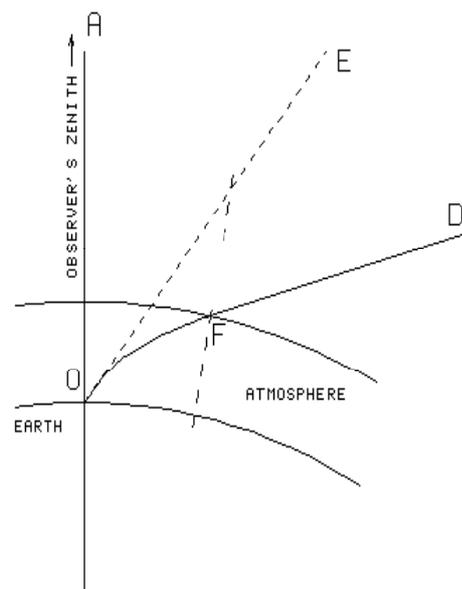
$$[n(\lambda) - 1] \times 10^6 = 64.328 + \frac{29498.1}{146 - \frac{1}{\lambda_0^2}} + \frac{255.4}{41 - \frac{1}{\lambda_0^2}}$$

(valid for dry air, 1 atm pressure, $T \sim 290\text{K}$ and λ_0 in $[\mu\text{m}]$).

1. **Refraction:** the apparent location of a star is significantly altered (up to half a degree near the horizon) \rightarrow telescope pointing model.

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

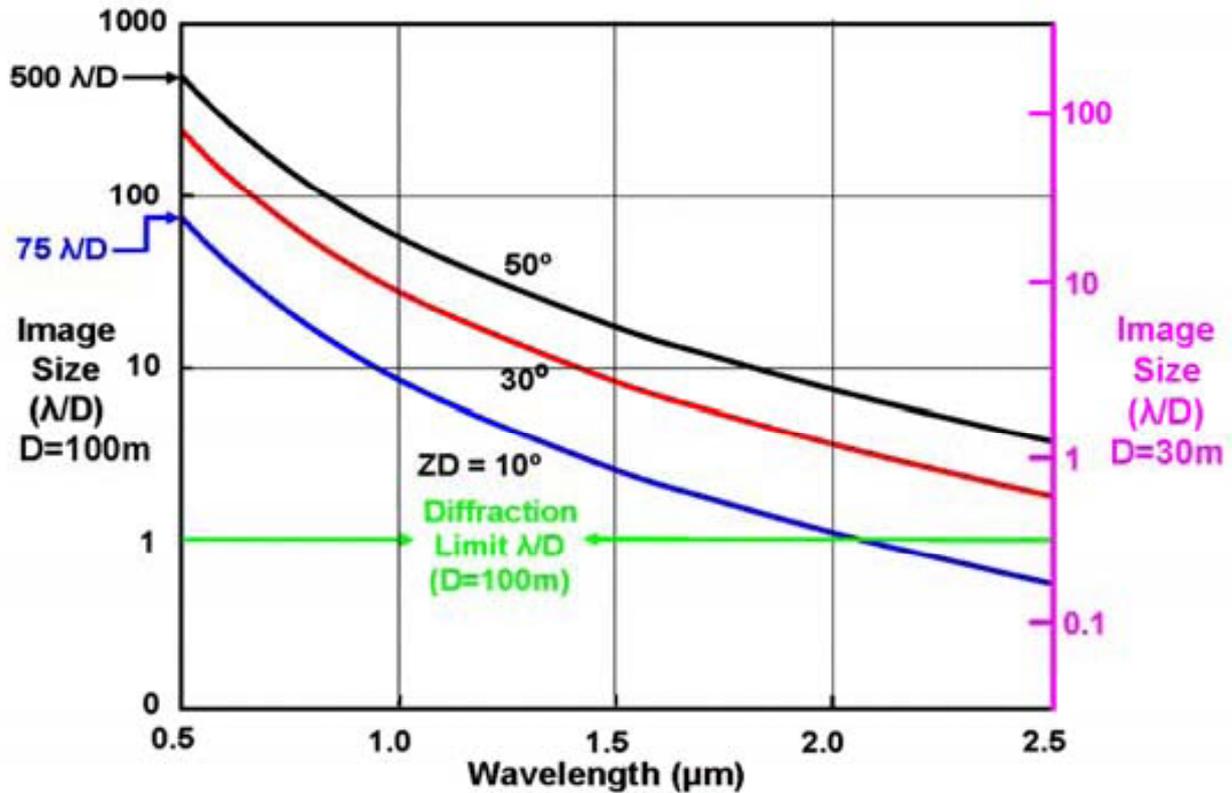
2. **Dispersion:** The elongation of points in broadband filters due to $n(\lambda)$ ["rainbow"]



Atmospheric Dispersion

No problem for small, seeing limited telescopes

Big problem for large diffraction limited telescopes



Atmospheric Dispersion Corrector

Atmosphere refracts light, so ...

1. use a refractive element (e.g., prism) to counterbalance refraction
2. use a second prism (different material with different dispersion) to maintain the optical axis
3. use a second (identical) double prism assembly to cover all zenith angles.

