

Atmospheric Optics

Lecture 1 – The Atmosphere

Outline

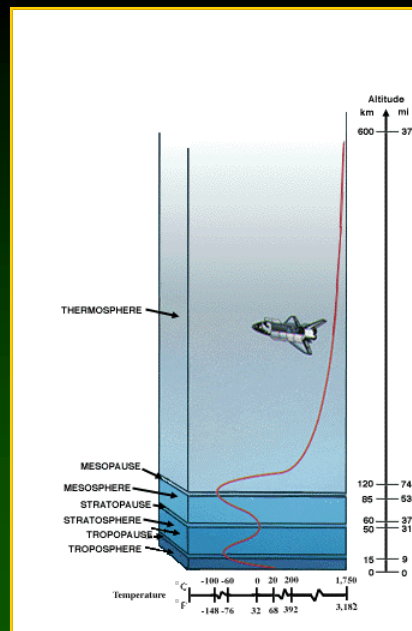
- Atmosphere
 - Layers
 - Composition
 - Gas
 - Particle
- Illumination
 - Passive
 - Solar
 - Active
- Properties of the Medium
 - Scattering
 - Dielectric
 - Index-of-refraction
 - Absorption
- Atmospheric Transmission
- Atmospheric Models
- Properties of Light
 - Polarization
 - Coherence
- Turbulence
 - Source
 - Parameters
 - Effect

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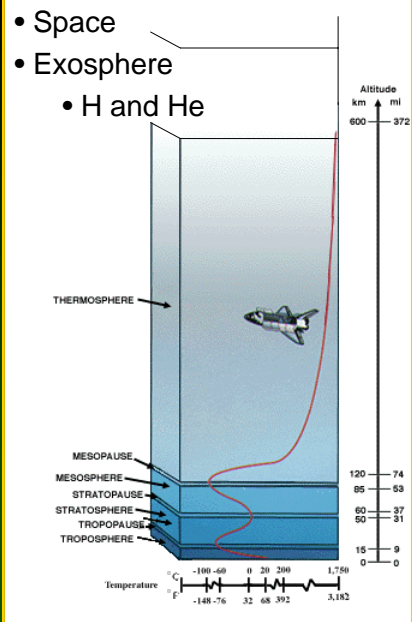
Atmospheric Layers

- Troposphere
 - Surface to 5-9 miles
 - Most dense
 - Almost all weather
- Stratosphere
 - Extends to 31 miles
 - Includes ozone layer
 - Absorbs UV
 - 99 % air below top of this layer



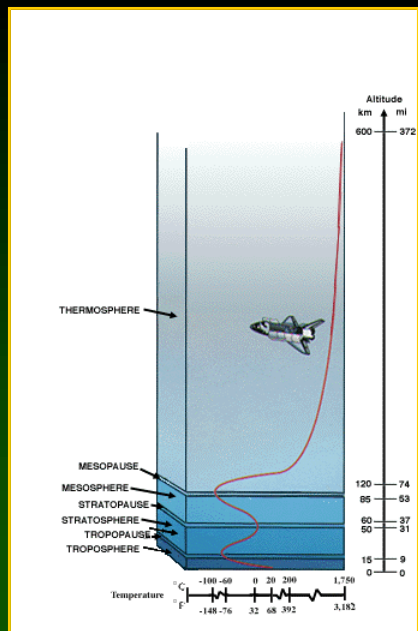
Atmospheric Layers (Cont.)

- Mesosphere
 - Extends to 53 miles
 - Chemicals in excited state
- Thermosphere
 - Extends to 372 miles
 - Chemical reactions occur quickly
- Pauses
 - Separate each layer

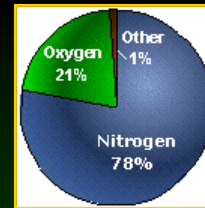


Atmospheric Layers (Cont.)

- Lower Atmosphere
 - Troposphere
 - Tropopause
- Middle Atmosphere
 - Stratosphere
 - Mesosphere
- Upper Atmosphere
 - Thermosphere



Gas Composition



- Uniformly mixed gases
 - Concentrations stable over time
 - N_2 , O_2 , Ar, Ne, He, Kr, Xe, H_2 , CH_4 , N_2)
- Gases present in variable amounts
 - O_3 , H_2O , CO_2 , CO, HNO_3 , NH_3 , H_2S , SO_2 , NO_2 , NO
- N_2 and O_2 most abundant
 - Abundance does not necessarily equate to importance

Particle Composition

- Vary in size and shape
- Size-distribution functions
 - Concentration as a function of particle radius
- Height-distribution functions
 - Concentration as a function of altitude
- Two classes of particles
 - Aerosol (radius $< 1\mu m$)
 - Suspended in the atmosphere (Most near surface of earth)
 - Increases scattering over molecular scattering
 - Hydrometers (radius $> 1\mu m$)
 - Water-dominated particles
 - Shorter lifespan

Aerosols

- Dust
 - Terrestrial
 - Volcanoes (Stratosphere)
 - Soil-based dusts
 - Industry and construction
 - Extraterrestrial (predominate in outer atmosphere)
 - Planetary accretion
 - Meteoroids
- Hygroscopic (depend on relative humidity)
 - Vegetation
 - Give off hydrocarbons which oxidize or nucleate into complex tars and resins
 - Sea
 - Sea salt (injected by bursting bubbles)
 - Concentration highly dependent on local wind velocity
 - Combustion by-products
 - Undergo photochemical reactions to produce hygroscopic particles

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Sun approximates a blackbody

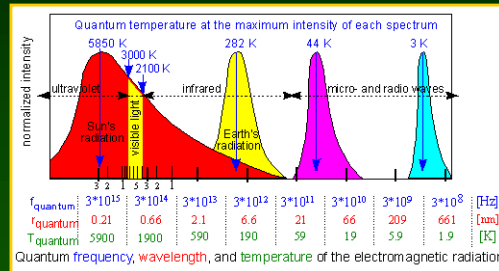
- Blackbody
 - Absorbs all incident flux
 - Re-radiates as described by the Planck equation

$$M_{\lambda} = 2\pi hc^2 \lambda^{-5} \left(e^{\frac{hc}{\lambda kT}} - 1 \right)^{-1}$$

M = spectral radiant exitance

- Stefan-Boltzmann
 - Over all λ

$$M_{Total} = \sigma T^4$$



- Wien Displacement Law
 - Maximum exitance

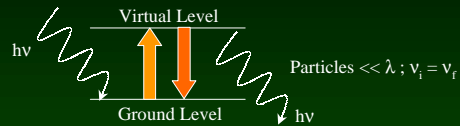
$$\lambda_{max} = \frac{A}{T}$$

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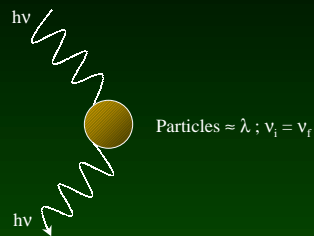
Scattering

- Rayleigh
 - Particles very small compared to wavelength
 - Shorter wavelengths scattered more than longer
 - Why sky is blue
 - Dominant scattering in upper atmosphere



Scattering

- Mie
 - Particles about the same size as the wavelength
 - Sunset (long path length)
 - Rayleigh - scatters blue light out of path
 - Mie - scatters the remaining yellow and red into the surrounding skies
 - Mostly in lower part of atmosphere



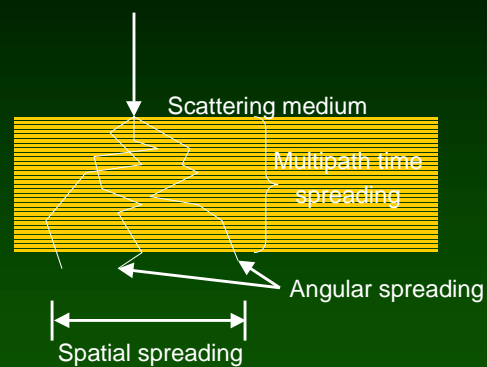
Scattering

- Non-selective
 - Particles much longer than the wavelength
 - All wavelengths scattered equally
 - Why fog and clouds appear white



Multiple Scattering

- Highly scattering medium
- Original radiance distribution undergoes
 - Angular spreading
 - Spatial spreading
 - Multipath temporal spreading
 - Reduced total transmission



Dielectric

- Dielectric - contains few or no free charges
 - In an EM field
 - Centers of the nonpolar molecules are displaced
 - Polar molecules become oriented close to the field
 - Charges appear at the boundaries of the dielectric
 - Frictional work done in orientation absorbs energy
 - A good dielectric is one in which the absorption is a minimum
 - Vacuum is the only perfect dielectric
 - Dielectric substance undergo refraction

Complex Index of Refraction

- Index of refraction (governs normal dispersion)

$$n = \frac{\text{velocity_in_vacuum}}{\text{velocity_in_medium}}$$

- Function of wavelength, temperature, and pressure
- If nonabsorbing and nonmagnetic at any wavelength, then $n^2 = \text{dielectric constant}$
- Complex index of refraction

$$n^* = n(1 - ik)$$

- $k = \text{absorptive index (governs absorption)}$

Absorption

- Light wave propagating through a medium

$$E = E_0 e^{i\left(\omega t - \frac{\omega n z}{c}\right)} e^{-\frac{\alpha k z}{c}}$$

propagation term decay term

- We measure intensity

$$I \propto |E_0|^2$$

$$I = I_0 e^{-\alpha z} = I_0 e^{-\frac{4\pi k z}{\lambda}}$$

- α = absorption or attenuation coefficient

Types of transitions

- Electronic
 - Visible (weak bands) and ultraviolet (strong bands)

- Vibrational

$$E_{El} > E_{Vib} > E_{Rot}$$

- Mid-infrared and near-infrared
 - Many narrow vibration-rotation absorption lines in the 5 μm to 12 μm region
- Rotational
 - Typically in the far-infrared

Types of Broadening

- Lorentz broadening (Lorentzian line profile)
 - Natural broadening
 - Due to finite lifetime of the energy states involved in the transition
 - Collision broadening
 - Due to elastic or inelastic encounters between the absorbing species and neighboring atoms
 - Holtsmark broadening - between like atoms or molecules
 - Van der Waals - between unlike species
- Doppler broadening (Gaussian line profile)
 - Due to thermal motion of the molecule
- Both types exist simultaneously (Voigt line function)
 - Resulting line profile is a convolution between the Lorentzian and Gaussian probabilities

Continuum Absorption/Emission

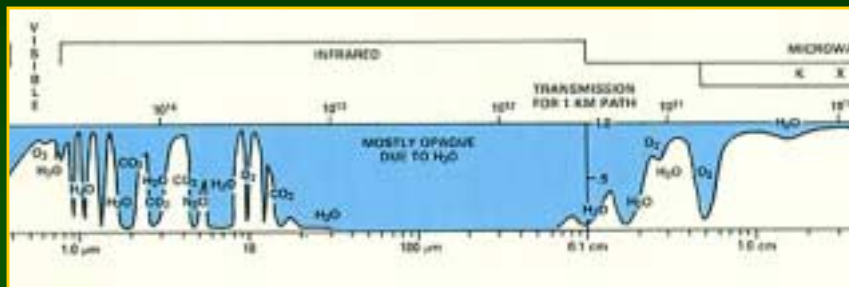
- Manifests itself in the infrared and millimeter wave window regions
 - Most notable for water-vapor
- Smooth frequency dependence
- Two main theories (not well understood)
 - Residual effects of the far wings of strong lines which are not accurately modeled
 - Molecular polymers, which are large floppy molecules, might be expected to have broad transitions and hence broad spectral features

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Atmospheric Windows

- Atmospheric constituents absorb differently as a function of wavelength
- The actual atmospheric transmission is a multiplication of all the individual transmissions



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AFRL Models

- HITRAN (high-resolution transmission molecular absorption)
 - Started development in the late 1960s
 - Line-by-line compilation of over 1,080,000 spectral line parameters for 36 different molecules
 - Parameters: line position, strength, half-width, lower energy level, etc.
 - Incorporated into LOWTRAN, MODTRAN, and FASCODE
 - Allow complex atmospheric transmittance and radiance calculations
 - Based on absorption and scattering phenomena for a variety of path geometries

AFRL Models

- LOWTRAN (low resolution transmittance code)
 - Single-parameter band model
 - Band model compute transmittance averaged over a spectral band (band model parameters every 5 cm^{-1})
 - 20 cm^{-1} resolution from 0 to $50,000 \text{ cm}^{-1}$
 - Does not fully represent the correct T dependence
 - Three classes of atmospheric gases
 - Water vapor, ozone, and uniformly mixed gases
 - Atmosphere is divided into 32 layers
 - 0 to $100,000 \text{ km}$ altitude
 - Layer thickness varies from 1 km to 30 km
 - Characteristics of each layer determined by inputs and standard models of various regions and seasons

AFRL Models

- LOWTRAN (low resolution transmittance code)
 - Calculations based on
 - LOWTRAN band model
 - Molecular continuum absorption
 - Molecular scattering
 - Aerosol absorption and scattering models
 - Includes
 - Atmospheric self-emission
 - Solar and/or lunar radiance single scattered into the path
 - Direct solar irradiance through a slant path to space
 - Multiple scattered solar and/or self-emission radiance into the path

AFRL Models

- MODTRAN (moderate resolution transmittance code)
 - Same as LOWTRAN except
 - Includes the two-parameter MODTRAN band model
 - Calculates atmospheric transmittance and radiance from 0 to 50,000 cm^{-1} at 2 cm^{-1} resolution
 - More realistic temperature-dependent model
 - Includes high-altitude transmittance/radiance calculations up to 60 km
 - Includes water vapor, carbon dioxide, ozone, nitrous oxide, carbon monoxide, methane, oxygen, nitric oxide, sulfur dioxide, ammonia, and nitric acid

AFRL Models

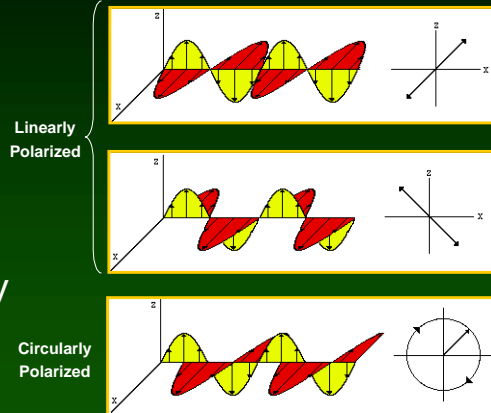
- FASCODE (fast atmospheric signature code)
 - High-resolution code
 - Uses the HITRAN database directly
 - Required for modeling very narrow optical bandwidth radiation such as a laser
 - Characterization of the aerosol and molecular medium is similar to LOWTRAN

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Polarization

- Light from the sun is unpolarized
- Molecules in the atmosphere act to polarize sunlight
- Light is most polarized 90° away from the sun
 - At sunset, light is most polarized directly overhead



Coherence

- Coherent light has the same wavelength and a constant phase relationship
- Laser light is coherent (active systems)
- Propagation through the atmosphere reduces the spatial coherence
 - Two points on a wave front separated by a distance greater than the coherence length are uncorrelated

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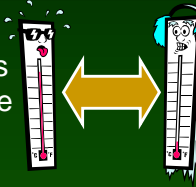
Source of Optical Turbulence



Wind and convection produce air motion



Air motion produces random temperature variations



Random temperature variations produce small index-of-refraction fluctuations



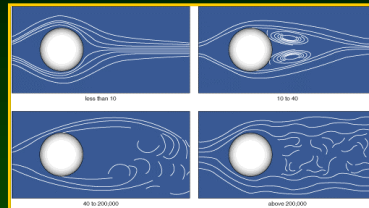
Index-of-refraction fluctuations

$$n = \frac{\text{velocity_in_vacuum}}{\text{velocity_in_medium}}$$

Optical = Turbulence

Source of Optical Turbulence

- Two regimes of fluid flow
 - Laminar
 - Each parcel of fluid stays nearly || to adjacent parcels
 - Turbulent
 - Portions of the flow move radially as well as axially, forming eddies and vortices
- Reynold's number – index of the tendency of the flow to become turbulent
 - Identified in 1883 by British engineer and physicist Osborne Reynolds



$$R = \frac{vL\rho}{\mu}$$

- v fluid velocity
- μ modulus of viscosity
- ρ density
- L characteristic length

<http://www.sigmaxi.org/amsci/articles/97articles/Hademenos-5.html>

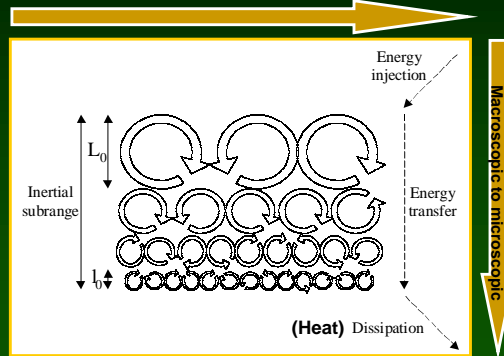
Source of Optical Turbulence

- Nonlinear process
 - Not derived from 1st principles
- Velocity of sections fluctuate about the mean velocity of the entire flow
 - Continuous power spectrum
 - Kolmogorov
 - Valid $1/L_0 \ll \kappa \ll 1/l_0$

$$\Phi_n(\kappa) = 0.033 C_n^2 \kappa^{-11/3}$$

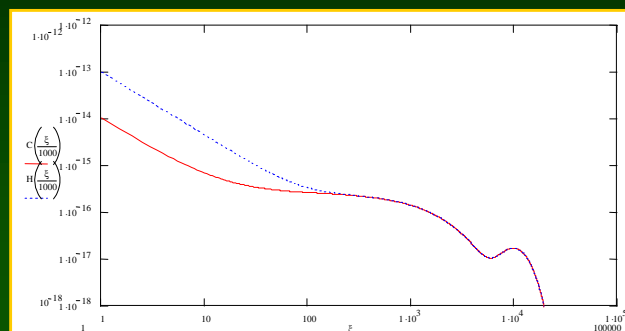
- Tatarskii
 - Valid $\kappa \gg 1/L_0$
- Von Kármán
 - Valid $0 \leq \kappa < \infty$

Wind – velocity increases until crosses from laminar to turbulent flow



Optical Turbulence Parameters

- Index-of-Refractive Structure Constant
 - Measure of turbulence strength



Optical Turbulence Parameters

- Several Models
 - Nonparametric
 - Submarine Laser Communication (SLC) Day and Night
 - Median values above Mt. Haleakala, Maui, Hawaii
 - All site specific
 - Parametric
 - Hufnagel (3-24 km)
 - Mid-latitude model, assumes a low tropopause
 - Since does not include the boundary layer can be used both day and night
 - Parameter = rms wind speed between 5-20 km in m/s
 - Hufnagel-Valley Model
 - Extension of Hufnagel model into the boundary layer
 - Parameters
 - » RMS wind speed between 5-20 km in m/s
 - » Value of C_n^2 one meter above the ground

Optical Turbulence Parameters

- Tatarski

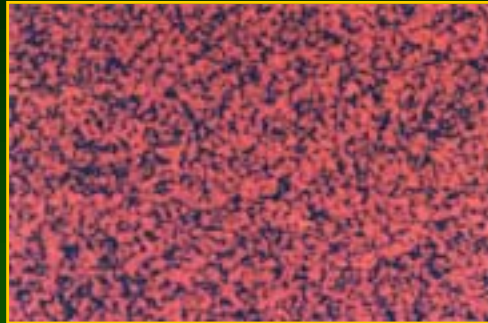
$$C_n^2 = 2.8L_0^{4/3} M^2$$

M = gradient of the refractive index
 L_0 = outer scale of turbulence

- NOAA (VanZandt) model
 - Excellent agreement with measurement
 - Most complex model and requires an expert to use
- Other simpler Tatariski-based models exist

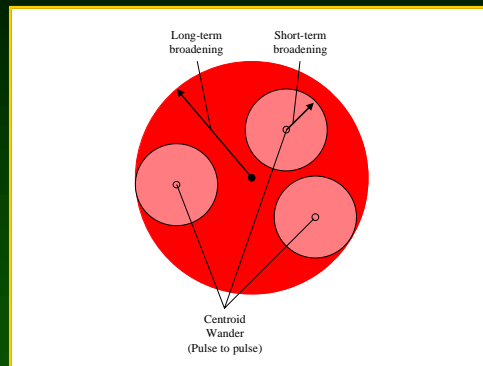
Effect of Optical Turbulence

- Scintillation
 - Spatial intensity fluctuations
 - Temporal intensity fluctuations
 - Speckle-like pattern
 - Responsible for twinkling of stars
 - Statistics of intensity are determined by those of log amplitude



Effect of Optical Turbulence – Phase Effects

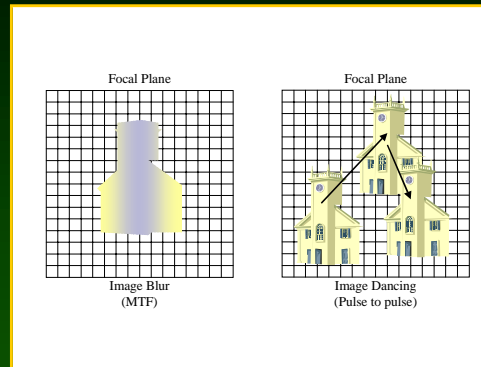
- Beam Spread
 - Scales small wrt beam size broaden the beam
- Beam Wander
 - Scales large wrt beam size cause tilt and deflect the beam



$$\langle \rho_L^2 \rangle = \langle \rho_s^2 \rangle + \langle \rho_c^2 \rangle$$

Effect of Optical Turbulence – Phase Effects

- Image Blurring
 - Counterpart to beam spread
- Image Dancing
 - Counterpart to beam wander



$$MTF(v) = \exp \left[-3.44 \left(\frac{\lambda f v}{r_0} \right)^{5/3} \right]$$

Effect of Optical Turbulence – Time Scale

- Assumes long-time averages
 - Average over eddies of all sizes
 - Phase spectra dominated by largest eddies
 - Eddies the size of the aperture move across at a rate of D/V
 - V = wind speed transverse to the propagation
 - D = aperture diameter
 - Exposures less than 0.01s usually considered short
- For a series of short exposures
 - Blur caused by small-scale eddies
 - Dancing caused by changes in the tilt from the large eddies

Effect of Optical Turbulence – Time Scale

- For a long exposure
 - Blur caused by superposition of the dancing and short-term blur
 - Includes effects from all scale sizes

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