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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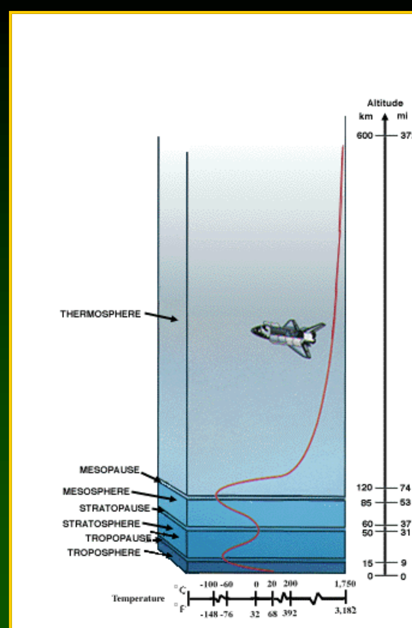
Atmospheric Layers

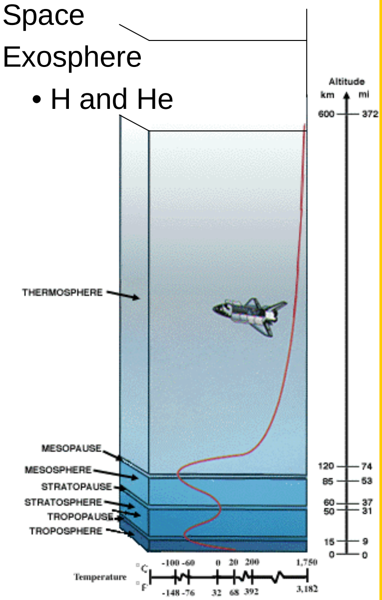
- Troposphere
  - Surface to 5-9 miles
  - Most dense
  - Almost all weather
- Stratosphere
  - Extends to 31 miles
  - Includes ozone layer
    - Absorbs UV
  - 99 % air below top of this layer



Atmospheric Layers (Cont.)

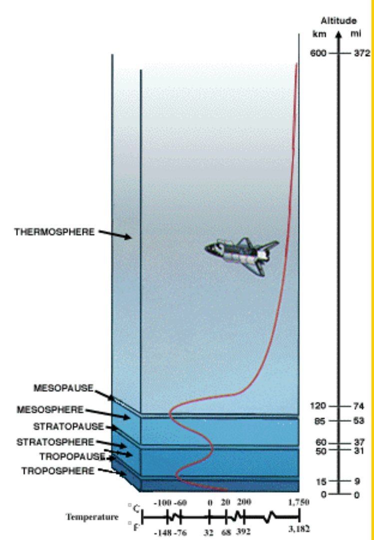
- Mesosphere
  - Extends to 53 miles
  - Chemicals in excited state
- Thermosphere
  - Extends to 372 miles
  - Chemical reactions occur quickly
- Pauses
  - Separate each layer

- Space
- Exosphere
  - H and He

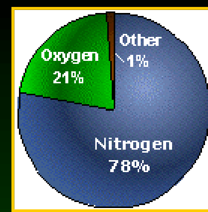


Atmospheric Layers (Cont.)

- 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 < 1μm)
    - Suspended in the atmosphere (Most near surface of earth)
    - Increases scattering over molecular scattering
  - Hydrometers (radius > 1μm)
    - 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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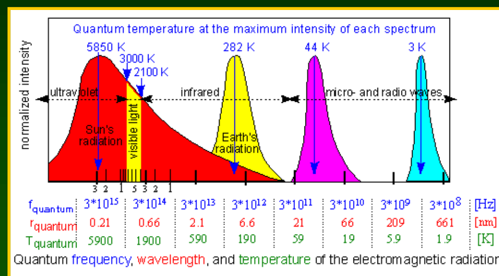
Sun approximates a blackbody

- 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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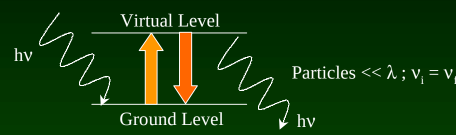
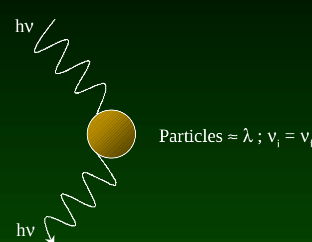
Scattering

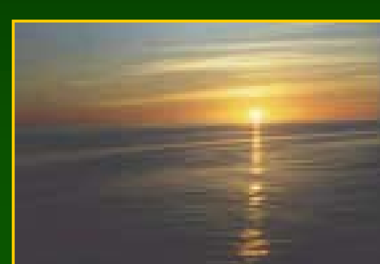
- Rayleigh
  - Particles very small compared to wavelength
  - Shorter wavelengths scattered more than longer
    - Why sky is blue
  - Dominant scattering in upper atmosphere



Scattering

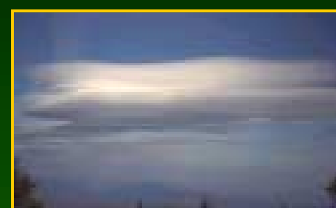
- Mie
  - Particles about the same size as the wavelength
  - Sunset (long path length)
    - Rayleigh - scatters blue light out of path
    - Mie - scatters the remaining yellow and red into the surrounding skies
  - Mostly in lower part of atmosphere





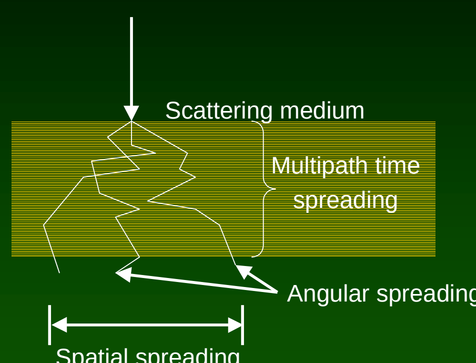
Scattering

- 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)

$$\boxed{n = \frac{velocity\_in\_vacuum}{velocity\_in\_medium}}$$

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

$$\boxed{n^* = n(1 - ik)}$$

  - k = absorptive index (governs absorption)

Absorption

- Light wave propagating through a medium

$$E = \underbrace{E_0 e^{i\left(\omega t - \frac{\omega n z}{c}\right)}}_{\text{propagation term}} \underbrace{e^{-\frac{\omega k z}{c}}}_{\text{decay term}}$$

- We measure intensity

$$I \propto \left|E_0\right|^2 \qquad I = I_0 e^{-\alpha z} = I_0 e^{-\frac{4\pi k z}{\lambda}}$$

  - α = absorption or attenuation coefficient

Types of transitions

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

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

- Vibrational
  - 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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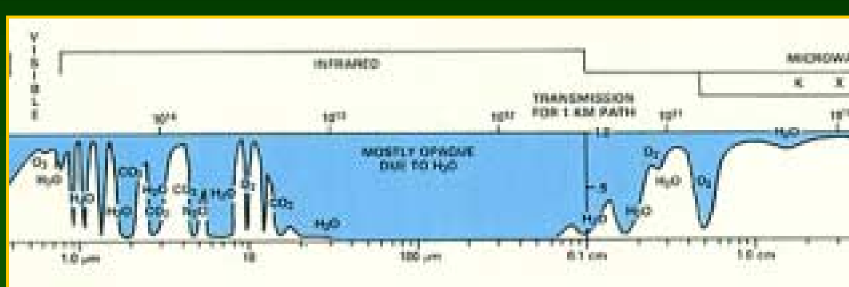
Atmospheric Windows

- 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 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 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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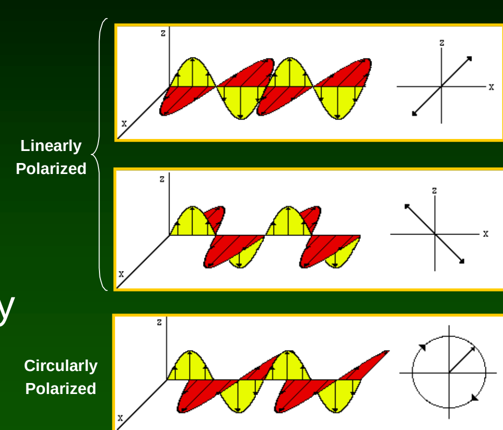
Polarization

- 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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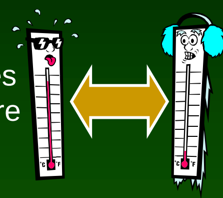
Source of Optical Turbulence

Wind and convection produce air motion

Air motion produces random temperature variations



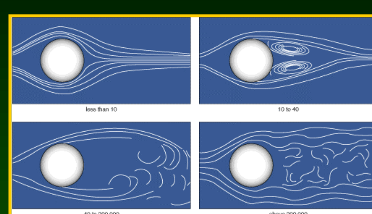
Random temperature variations produce small index-of-refraction fluctuations

$$n = \frac{velocity\_in\_vacuum}{velocity\_in\_medium}$$

Index-of-refraction fluctuations = 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

$$R = \frac{\upsilon L \rho}{\mu}$$

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

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

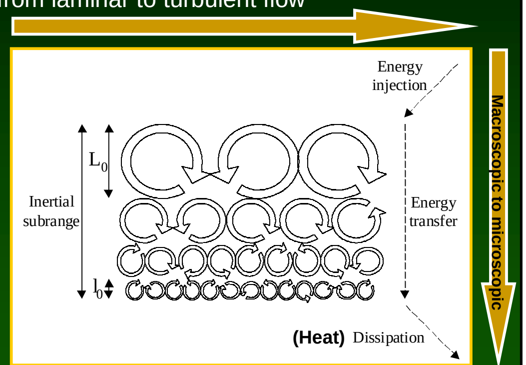
Source of Optical Turbulence

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

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

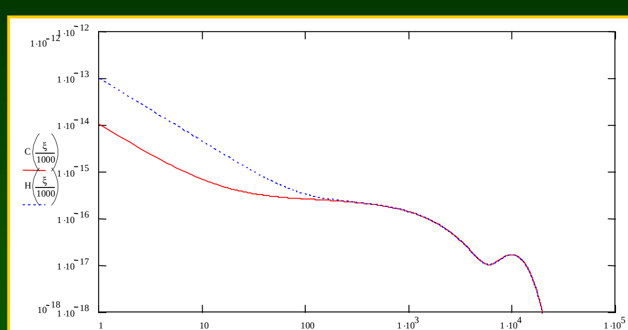
  - Tatarskii
    - Valid $\kappa >> 1/L_0$
  - Von Kármán
    - Valid $0 \leq \kappa < \infty$

Wind – velocity increases until crosses from laminar to turbulent flow



Optical Turbulence Parameters

- Index-of-Refraction 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

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

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

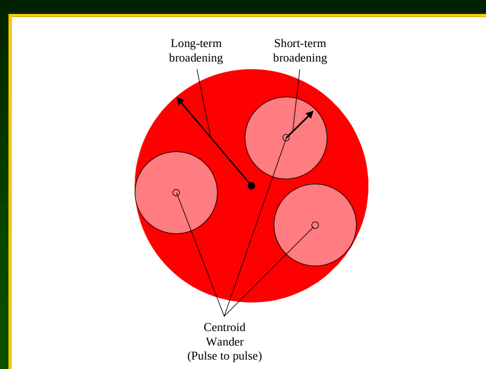
- NOAA (VanZandt) model
  - Excellent agreement with measurement
  - Most complex model and requires an expert to use
- Other simpler Tatariski-based models exist

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

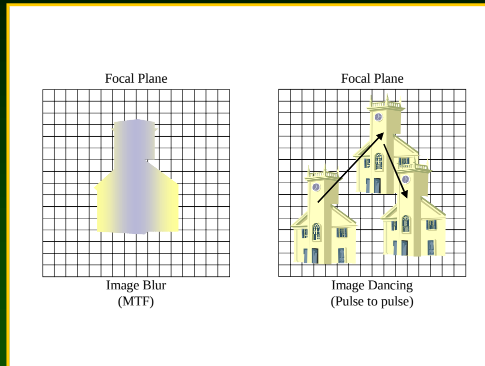
- Beam Spread
  - Scales small wrt beam size broaden the beam
- Beam Wander
  - Scales large wrt beam size cause tilt and deflect the beam



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

Effect of Optical Turbulence – Phase Effects

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



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

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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The End