



MET 4410 Remote Sensing: Radar and Satellite Meteorology
MET 5412 Remote Sensing in Meteorology

**Lecture 3: Introduction to Atmospheric
Radiation (Petty book Ch1-2)**

Lec 3: Part 1

What is Atmospheric Radiation?

- Definition:
 - The study of all radiation process affecting the earth's atmosphere.
- The discipline examines:
 - The **absorption, emission, and scattering** of electromagnetic (EM) radiation within the atmosphere;
 - The nature and distribution of incident solar radiation at the top of the atmosphere;
 - The reflection and emission from the surface at the bottom of the atmosphere.

What is Atmospheric Radiation?

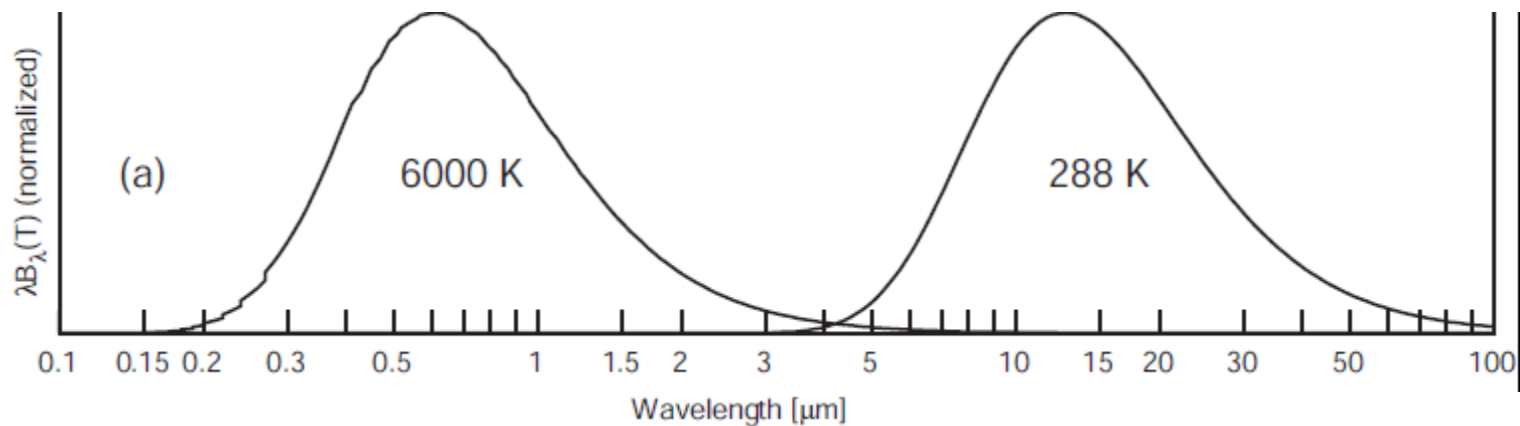
(Cont.)

- Two main areas:
 - The effect of radiative heating or cooling on temperature, thereby helping to define the basic structure of the earth's climate system. (This is not the focus of this course)
 - Use of the information content in measured radiation to deduce properties of the atmosphere or surface -- **Remote sensing!**
- Energy transfer in the atmosphere involves radiation in two distinct bands of wavelength: shortwave and longwave radiation.

Shortwave (Solar) Radiation

- Definition:

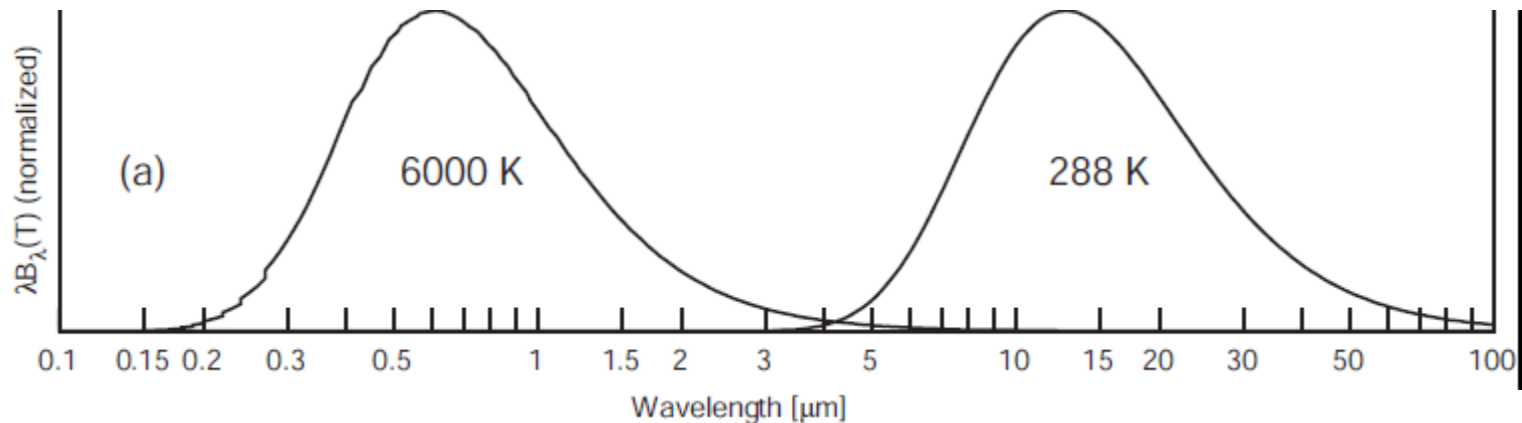
- Is the radiation emitted by the Sun.
- Wavelength: peak at visible around at $\lambda=0.5-0.6\mu\text{m}$
tails: infrared (IR) $\lambda >0.7\mu\text{m}$
Ultraviolet (UV) $\lambda <0.3\mu\text{m}$



Longwave (Thermal) Radiation

- Definition:

- Is the radiation emitted by the Earth's surface and atmosphere.
- Wavelength: peak at IR around $\lambda=10-15\mu\text{m}$
tails: IR $\lambda \cong 5\mu\text{m}$

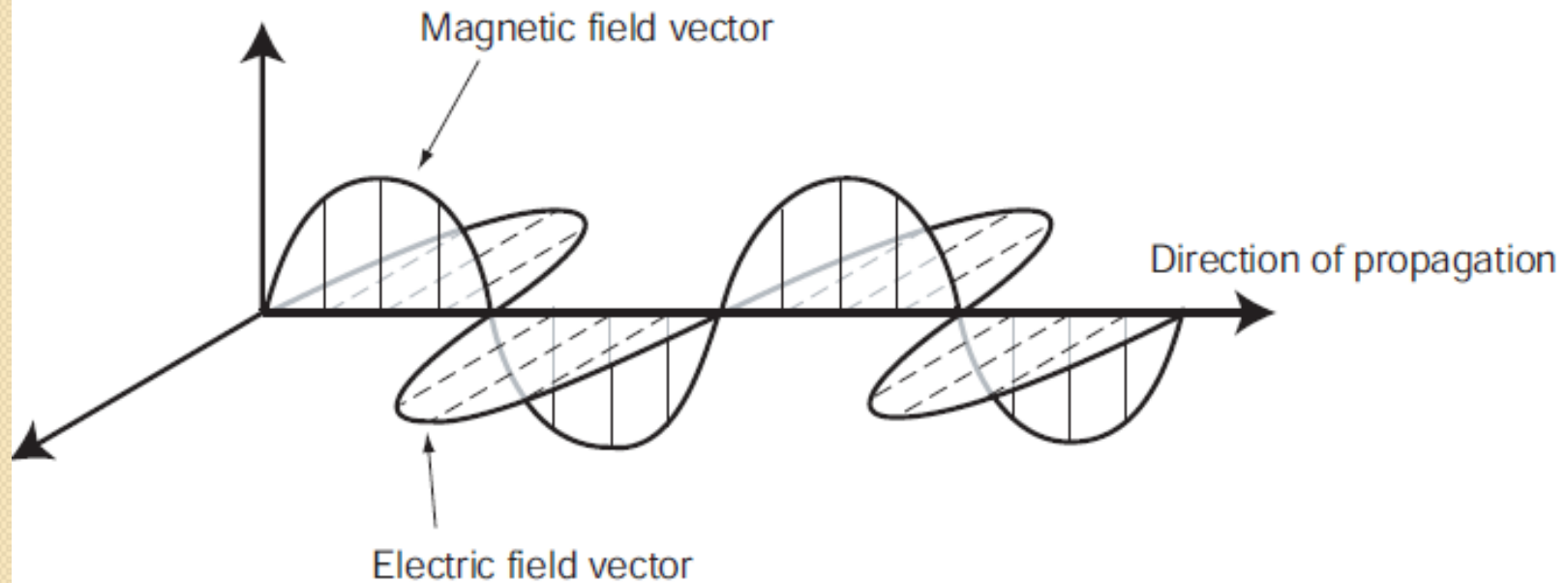


Properties of Radiation

- Electromagnetic (EM) wave:
 - **Static electric field** is determined by the distribution of electric charge
 - **Static magnetic field** is determined by the distribution of electric current (moving electric charge) in the neighborhood.
 - **Related law:** a changing magnetic field induces an electric field that can drive a current; a changing electric field induces a magnetic field.
 - EM wave: a changing in either an electric or magnetic field leads to a disturbance that is self-perpetuating, which is an EM wave.
 - Example: moving a magnet on a table and sticking it to a refrigerator will induce an EM wave (Petty book pg. 11).

EM Radiation (Wave)

- Definition:
 - EM wave consists of alternating electric and magnetic fields.
 - The electric field is perpendicular to the magnetic field vector, and the direction of propagation is perpendicular to both.

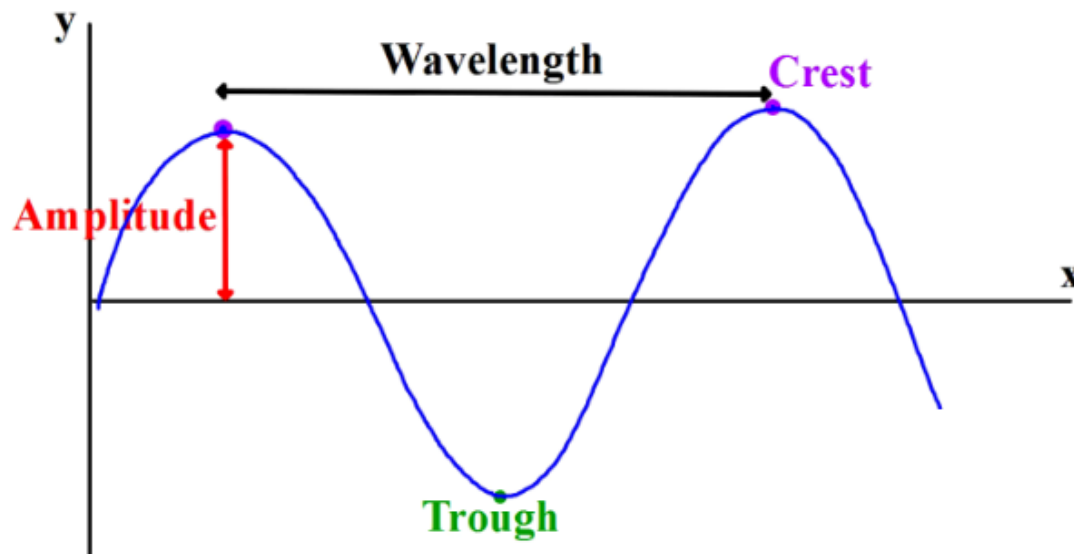


Characteristics of EM waves

- EM waves always travel in a vacuum at an absolutely constant speed: the speed of light $c=3 \times 10^8$ m/s
- EM waves require no material medium in which to propagate (pond ripples need a pond to propagate, sound needs air to propagate).
- Interacting with matters (such as the atmosphere and its various resident particles) makes the propagation of EM waves more complex and interesting.
- EM waves propagate in 3D space. The orientation of the electric field vector may lie in any direction, as long as it is in a plane normal to the direction of propagation.
- EM waves are transverse waves (sound waves are longitudinal).
- EM waves can transport energy.

Basic Quantities to describe EM waves

- Wavelength λ : radiation is specified by its wavelength, which is the distance between crest of the electric or magnetic field.
Unit: nm (10^{-9} m); μm (10^{-6} m); cm (10^{-2} m)



Basic Quantities to describe EM waves

- Frequency f : is the rate at which the electric or magnetic field oscillates when observed at a point: $f = \omega / 2\pi$, where ω is the angular speed. Frequency has units: of cycles per second, or Hertz (Hz, s^{-1}). Frequency is related to wavelength by: $f = \frac{c}{\lambda}$.
- Wavenumber: $K = 1/\lambda$, is the reciprocal of wavelength.
- Notes:
 - When the EM radiation interacts with mediums (matters), its wavelength decreased due to the speed of radiation slower than c , but its frequency stays unchanged (assume that the observer is at a fixed distance from the radiation source. Otherwise the frequency will be shifted by the Doppler effect.)
 - The reason EM waves travel slower is the effect that the electrons have on the waves. They act somewhat like a “friction” on the waves.

Index of Refraction

- Index of refraction, n , of a substance is the ratio of the speed of light in a vacuum to the speed with which EM radiation travels in that substance.
- At seas level, the index of refraction of air is about 1.0003

Energy

- EM waves can transport energy. The energy of an EM wave is quantized. A wave consists of discrete packets of energy called photons. The energy per photon is:

$$E = hf \quad (\text{Planck-Einstein equation})$$

where h is Planck's constant, $h = 6.626 \times 10^{-34} \text{ J S}$. f is frequency.

- Frequency is proportional to energy.
- The quantum description of EM radiation and the previous wave description is a paradox to be solved.
- However, what you should know is:
 - The wave nature of radiation matters when computing the scattering and reflection properties of atmospheric particles and surfaces.
 - The quantum nature of radiation matters when considering absorption and emission of radiation by individual atoms and molecules, including photochemical reactions.
 - For calculations of large-scale transportation of radiation in the atmosphere, the effects of both types of interactions will have already been deeply buried in some generic extinction and scattering coefficients.

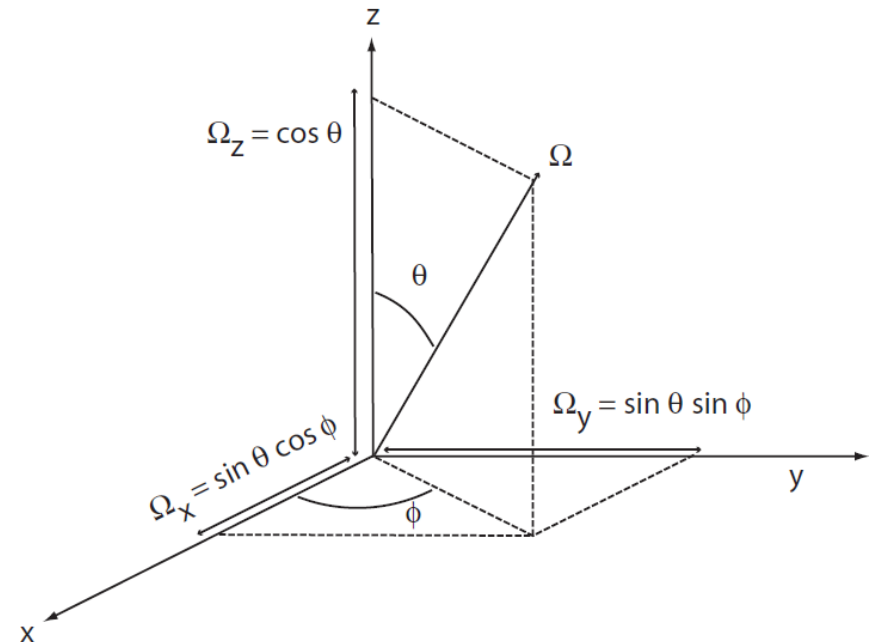
Lec 3: Part 2

Measures of Energy

- Radiant Energy: Unit: *Joule (J)*
- Power (rate of energy transfer, some books call it “radiant flux”, but to void confusion with the “flux density” below, we will call it power): is the radiant energy per unit time. Unit: *Watts (W) = J/s*
- Flux density (or flux for short): is the radiant power per unit area. Unit: W/m^2 . According to which way the energy is traveling, flux is subdivided into:
 - Radiant exitance: is radiant flux density emerging from an area
 - Irradiance: is radiant flux density incident an area
- Intensity: is the most important measure of radiation energy. It includes the direction information. It will be defined after we introduce solid angle.

Spherical Polar Coordinates

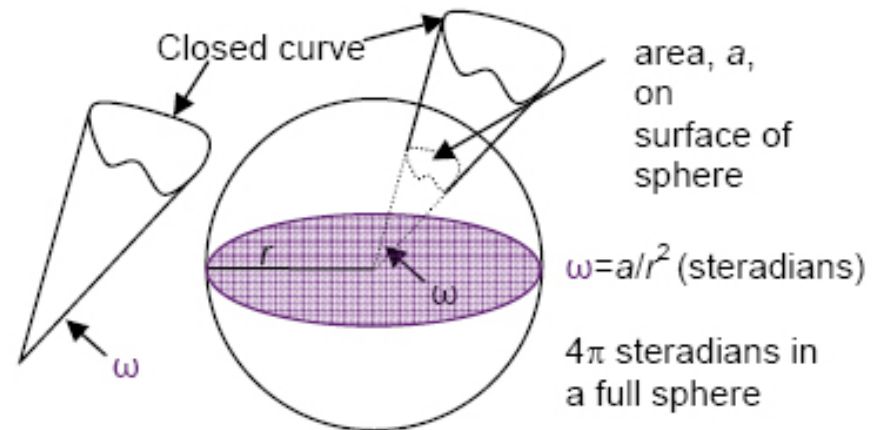
- Zenith Angle θ : measures the angle from the local vertical. The range of θ is only from 0 to π (not from 0 to 2π)
 - $\theta=0^\circ$ directly overhead, vertical
 - $\theta=90^\circ$, horizon
 - $90^\circ < \theta < 180^\circ$, direction below horizon
 - $\theta=180^\circ$, nadir
- Azimuthal Angle ϕ : measures the angle counterclockwise from a reference point on the horizon. The range of ϕ is only from 0 to 2π .



Petty book Fig. 2.3: The relationship between Cartesian and spherical coordinates.

Solid Angle

- Definition of solid angle: If one draw lines from the center of the unit sphere to every point on the surface of an object, the area of the projection on the unit sphere is the solid angle. The solid angle of an object that completely surrounds a point is 4π steradians (sr). If the projected area A is on any sphere with radius r , then the solid angle is: $\omega = A/r^2$
- Solid angle is a measure of how much your visual field of view is occupied by an object.
- The unit of solid angle is steradian (sr).
- The solid angle subtended by an infinite plane is 2π sr.



Understanding Solid Angle

- Solid angle is to “regular” angle as area to length.
- Steradian is something like “square radian” or “square degree”. Solid angle is like “2D angular dimension”.
- Mathematically, recall the definition of regular angle in radian, which is:

$$\theta = \frac{l}{r}, \text{ for a whole circle, } l = 2\pi r, \text{ then}$$

$$\theta = \frac{2\pi r}{r} = 2\pi$$

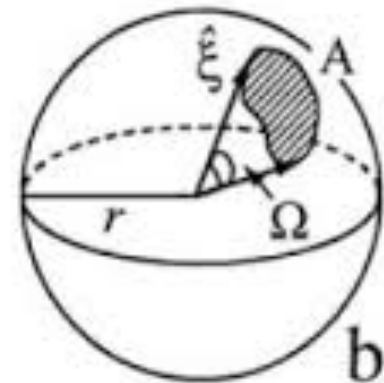
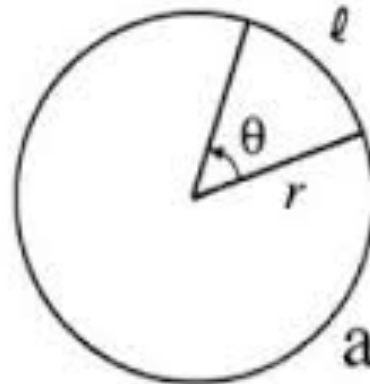
- Analogically, solid angle

$$\omega = \frac{A}{r^2}$$

Where A is the cross-sectional area of the object, and r is the distance from the origin (or the observation point).

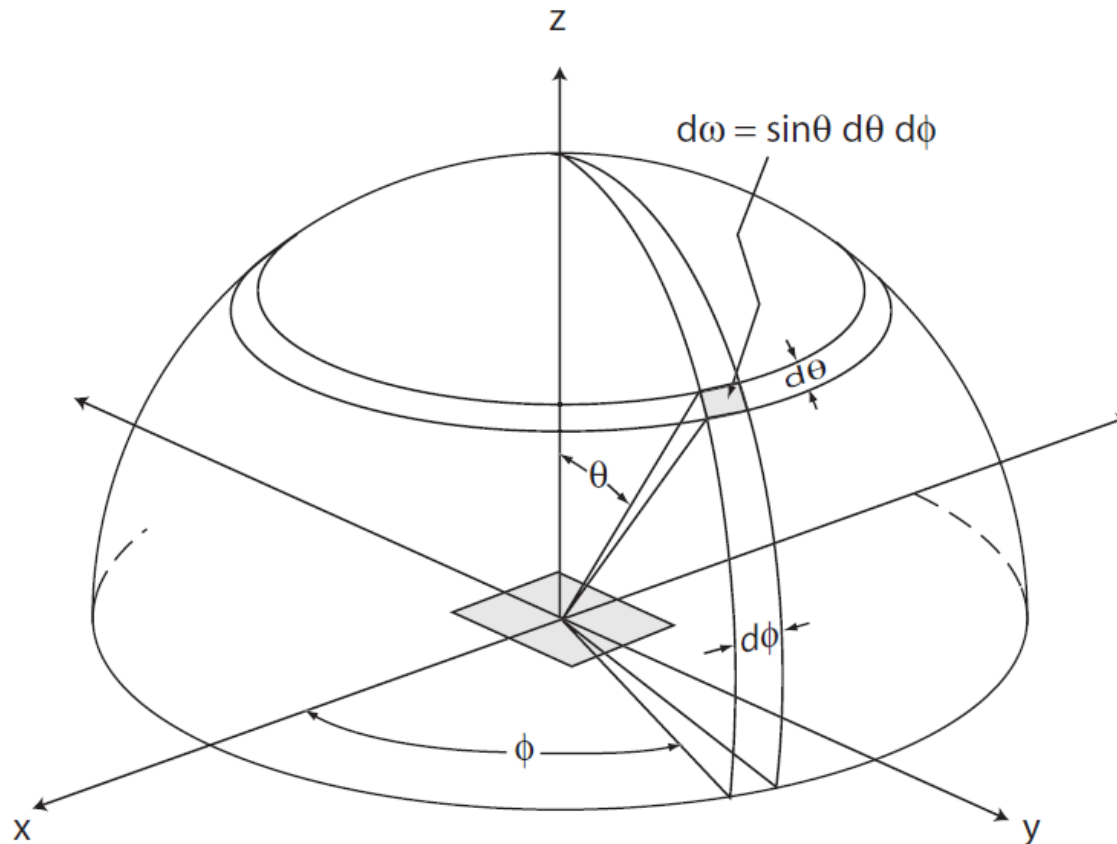
- For a whole sphere, $A = 4\pi r^2$, then

$$\omega = \frac{4\pi r^2}{r^2} = 4\pi$$



Differential Element of Solid Angle

- If you paint an infinitesimal rectangle on the surface of a sphere, and it has angular dimensions $d\theta$ (zenith angle) and $d\phi$ (azimuthal angle), and is positioned at θ , then the infinitesimal increment of solid angle is as follow: $d\omega = \sin\theta d\theta d\phi$



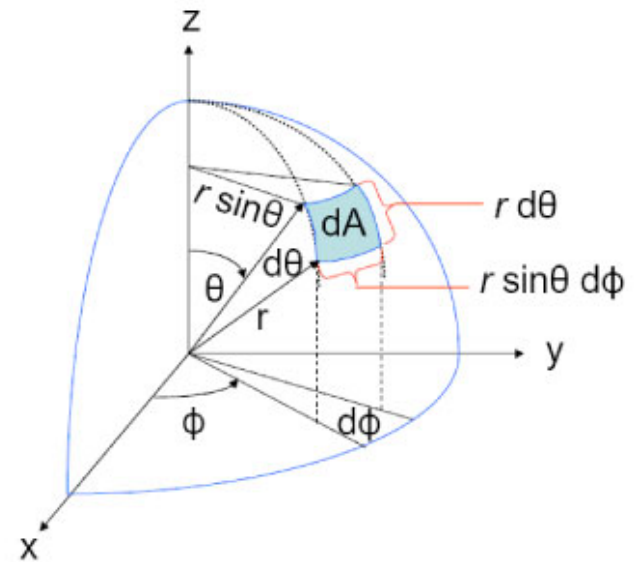
Derivation

- The area of infinitesimal rectangle is:

$$dA = (rd\theta) \cdot (r\sin\theta d\phi)$$

- Then the infinitesimal increment of solid angle is:

$$d\omega = \frac{dA}{r^2} = \sin\theta d\theta d\phi$$



- To demonstrate that the expected solid angle of the entire sphere is $4\pi sr$:

$$\int_{4\pi} d\omega = \int_0^{2\pi} \int_0^{\pi} \sin\theta d\theta d\phi = 2\pi \int_0^{\pi} \sin\theta d\theta = -2\pi \int_0^{\pi} d\cos\theta = -2\pi(\cos\pi - \cos 0) = 4\pi$$

- To understand why does $\sin\theta$ appear in $d\omega = \sin\theta d\theta d\phi$:
 - This is for the same reason that a 1 x 1 box is smaller near the North pole than near the equator.

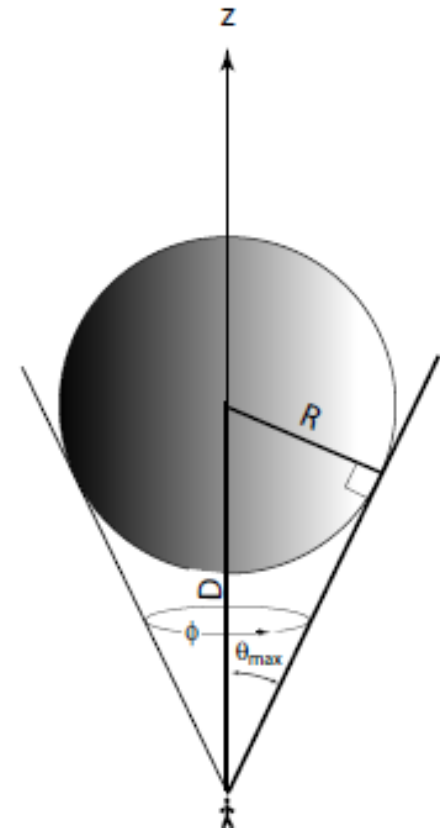
Measures of Energy (cont.)

- Intensity (or radiance): is the radiant flux density (or flux for short) per unit solid angle traveling in a particular direction. Here flux is measured on a surface normal to the radiation beam. Unit: $\text{W m}^{-2} \text{sr}^{-1}$.
- Visualizing this definition as follows:
 - Looking in a particular direction, identifying a very small element of the scene with solid angle $\delta\omega$.
 - Measure, normal to the beam, the flux δF of radiation arriving just from that small region, which excluding all other contributions.
 - The intensity in that particular direction is then given by:

$$I = \frac{\delta F}{\delta\omega}$$

Conservation of Radiance (Intensity)

- Intensity (or radiance): is independent of distance from an object as long as the view angle and the amount of intervening matter are not changed
 - Consider a satellite viewing a small object. The irradiance (flux density or flux) reaching the satellite from the object will decrease inversely as the square of the distance of the satellite.
 - However, the solid angle of the object subtended at the satellite will also decrease inversely as the square of the distance of the satellite.
 - Since the radiance of the object as viewed by the satellite is simply the irradiance (flux) divided by the solid angle: $I = \frac{F}{\omega}$, so the radiance is independent of distance.



Broadband vs. Monochromatic Radiation

- EM radiation composed entirely of a single frequency is termed **monochromatic** (“one color”), also called **coherent**.
- Radiation that consists of a mixture of a wide range of frequency is called **broadband** radiation, also called **incoherent**.
- Natural radiation is **broadband and incoherent**.
- Radiation from artificial sources used in remote sensing is **monochromatic and coherent**.
- The flux and intensity of natural (incoherent) radiation expressed simply in W m^{-2} and $\text{W m}^{-2} \text{sr}^{-1}$ must be a broadband quantity.
- **Monochromatic (spectral) flux** F_λ : should be *power per unit area per unit wavelength*: $\text{W m}^{-2} \mu\text{m}^{-1}$. Broadband flux between a range of wavelength $[\lambda_1, \lambda_2]$ is :

$$F(\lambda_1, \lambda_2) = \int_{\lambda_2}^{\lambda_1} F_\lambda d\lambda$$

Monochromatic (Spectral) Radiance/Intensity

- **Monochromatic Intensity** I_λ : is the *energy per unit time per unit wavelength per solid angle crossing a unit area perpendicular to the beam* (or simply the radiance or intensity per wavelength). Unit: $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$. Because broadband radiance or intensity is simply the integral over all wavelengths of monochromatic radiance or intensity, we must have:

$$I = \int_0^{\infty} I_\lambda d\lambda$$

- The most fundamental radiation unit for satellite meteorology is monochromatic radiance. The basic satellite instrument, radiometer, measures a quantity that is most closely related to monochromatic radiance.

Relationship between Flux and Intensity

- The flux incident on, passing through, or emerging from an arbitrary surface is given by an integral over the relevant range of solid angle of the intensity (or radiance).
- To calculate the flux emerging upward from a horizontal surface:
 - It must be an integral of the intensity over all possible directions directed skyward, i.e., into 2π Sr of solid angle corresponding to the upper hemisphere.
 - Since intensity is defined in terms of flux per unit solid angle normal to the beam, we must weight the contributions to the flux by the cosine of the incident angle relative to the normal vector.

Relationship between Flux and Intensity

- Therefore, the upward-directed flux:

$$F^\uparrow = \int_0^{2\pi} I^\uparrow(\theta, \varphi) \cos\theta d\omega$$

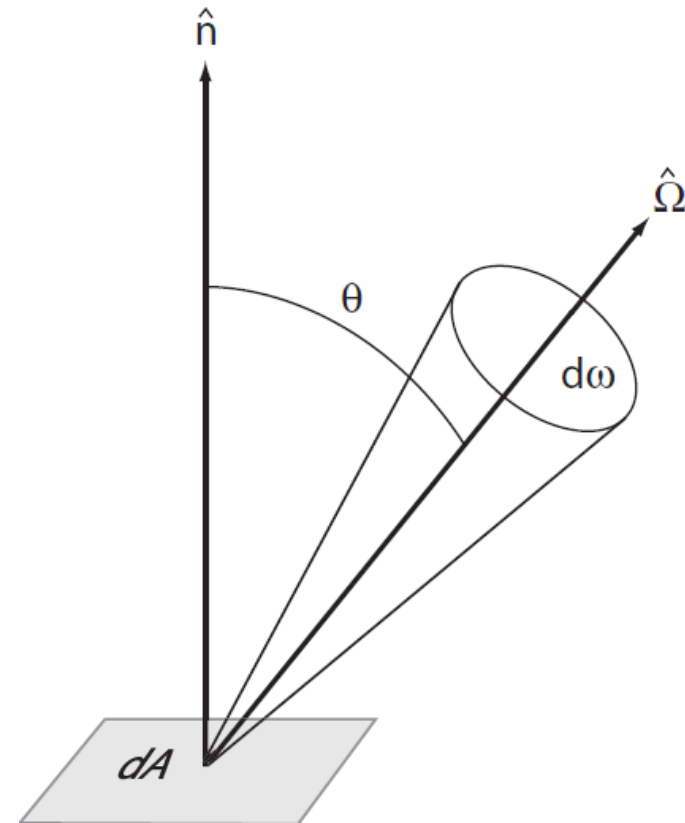
$$F^\uparrow = \int_0^{2\pi} \int_0^{\pi/2} I^\uparrow(\theta, \varphi) \cos\theta \sin\theta d\theta d\varphi$$

- For the downward flux, we integrate over the lower hemisphere:

$$F^\downarrow = - \int_0^{2\pi} \int_{\pi/2}^{\pi} I^\downarrow(\theta, \varphi) \cos\theta \sin\theta d\theta d\varphi$$

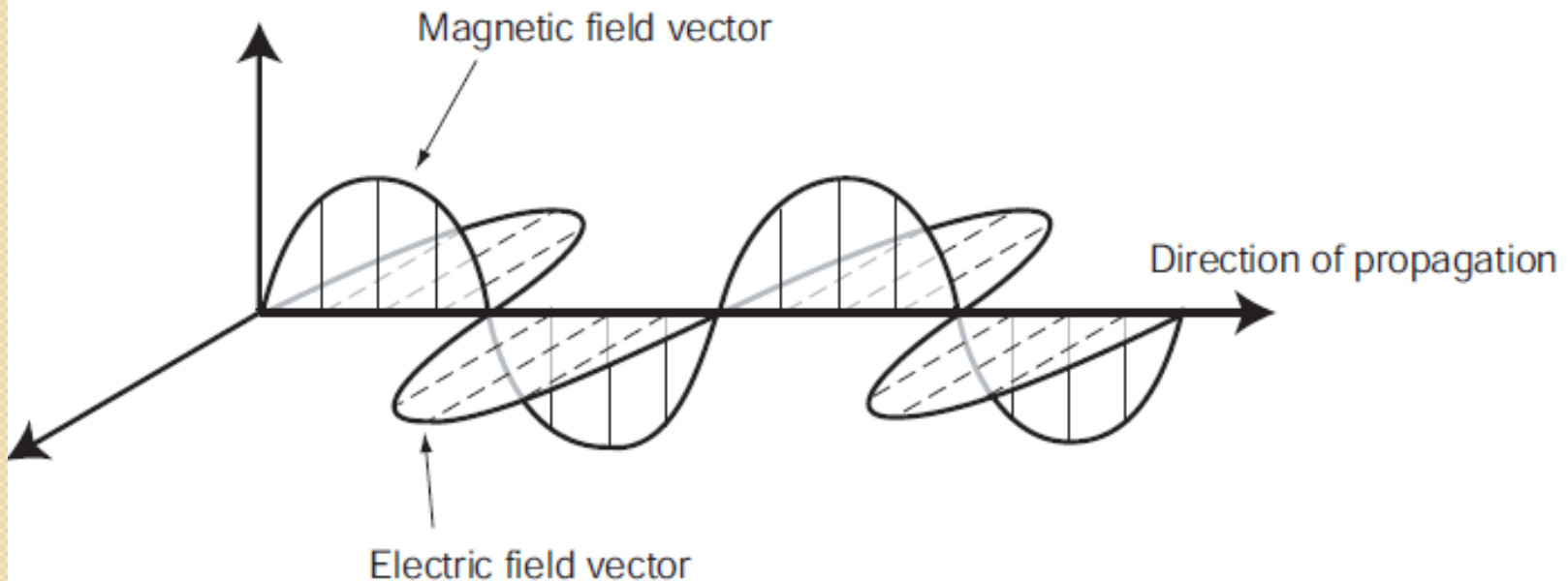
- For isotropic radiation (i.e., if the radiance/intensity is independent of direction):

$$F^\downarrow = F^\uparrow = \pi I$$



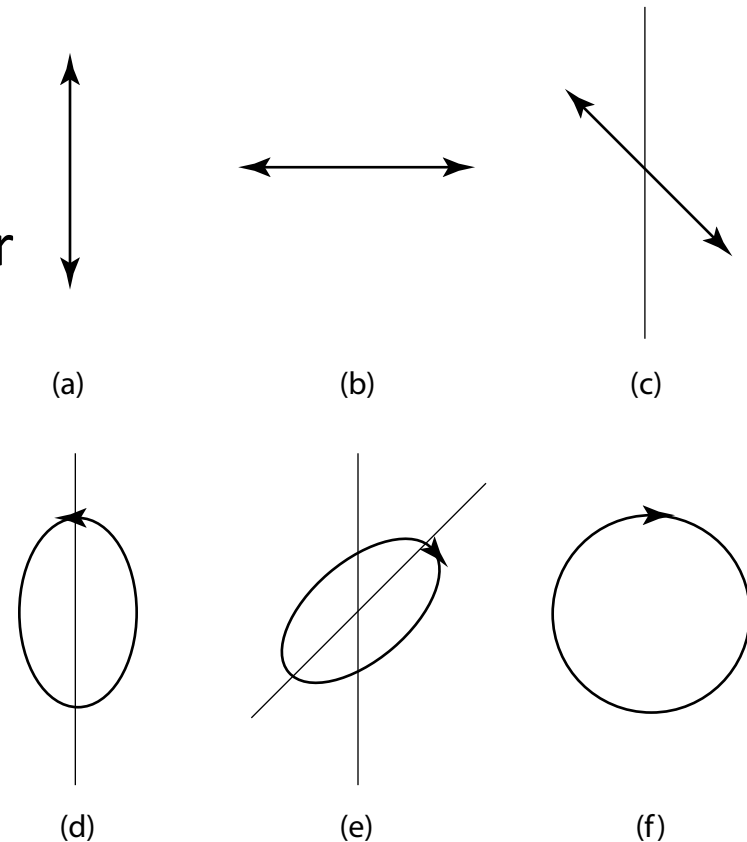
Polarization

- The orientation of the oscillating electric field vector in a EM wave can be any direction that is perpendicular to the direction of propagation.
- Polarization: is to keep track of that orientation and how it evolves over the course of a complete cycle.



Polarization

- In coherent radiation, there is a unique, repeating pattern to the oscillating electric field vector when viewed along the direction of propagation.
- **Linear Polarization:** It vibrates back and forth in a fixed plane, like a pendulum or plucked guitar string: (a)–(c). **(a) is vertical polarization, (b) is horizontal polarization.**
- **Circular Polarization:** It vibrates in a spiral fashion about the direction of propagation, either clockwise or counterclockwise: (f)
- **Elliptical Polarization:** is a hybrid of the first two (d)-(e)



Polarization

- Standard weather radar equipment typically transmits coherent radiation with linear polarization (either vertical or horizontal) and then measures the backscattered radiation with the same polarization.
- More sophisticated radars (i.e., **Dual-Polarization Radar**) may transmit in one polarization but then separately measure the returned radiation in both vertical and horizontal polarizations in order to gain additional information about the targets
- As a general rule, natural emissions of radiation in the atmosphere are completely unpolarized, but the radiation may become partially or completely polarized in the course of its interactions with particles and/or the surface.
- In particular, a smooth surface, like calm water, preferentially reflects radiation having horizontal linear polarization. This is the phenomenon that motivated the invention of polarized sunglasses, which block the reflected horizontally polarized radiation while transmitting the rest. It is also a phenomenon of great practical importance for satellite remote sensing in the microwave band.