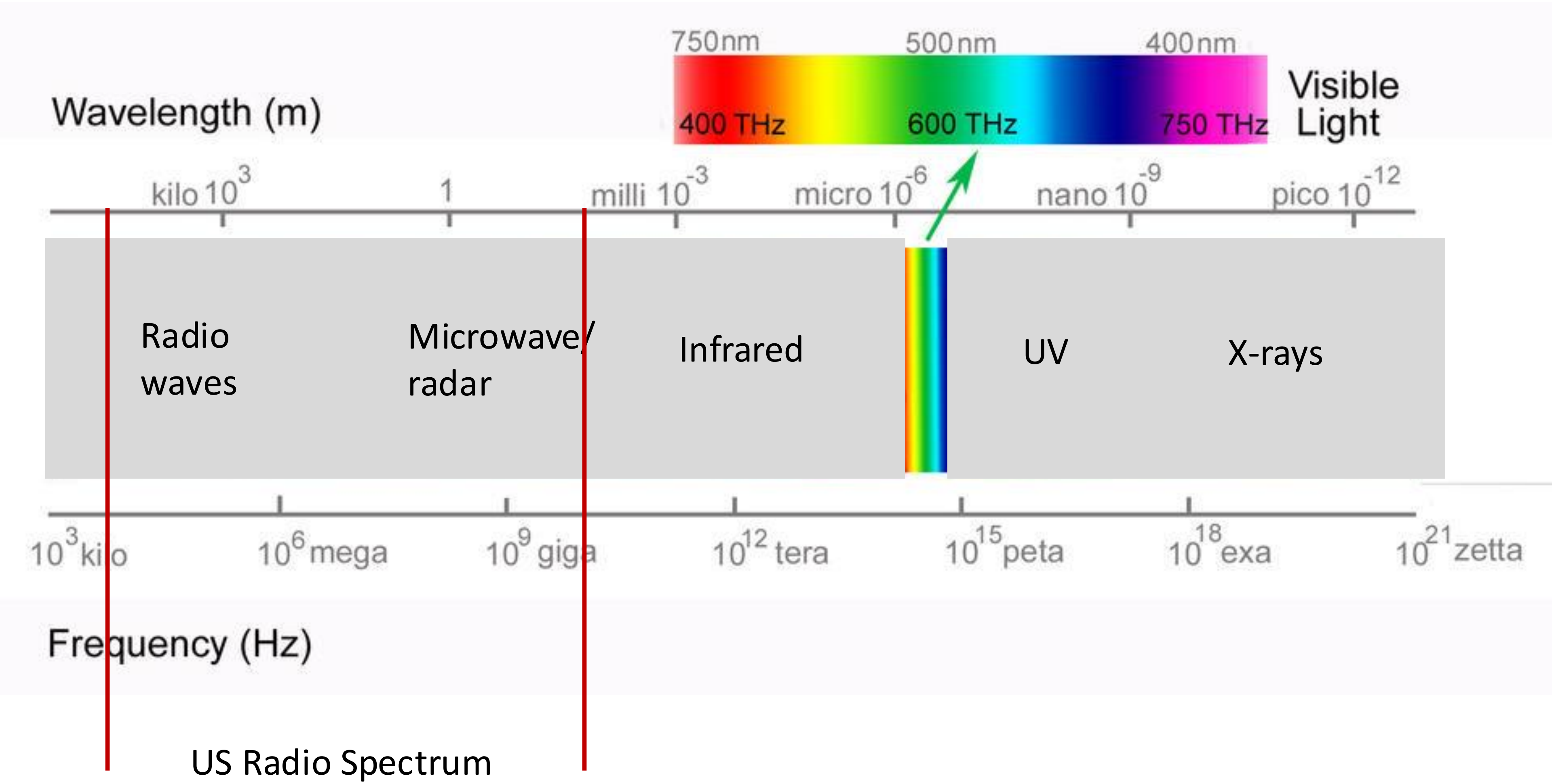
MR3522: Remote Sensing of the Atmosphere and Ocean

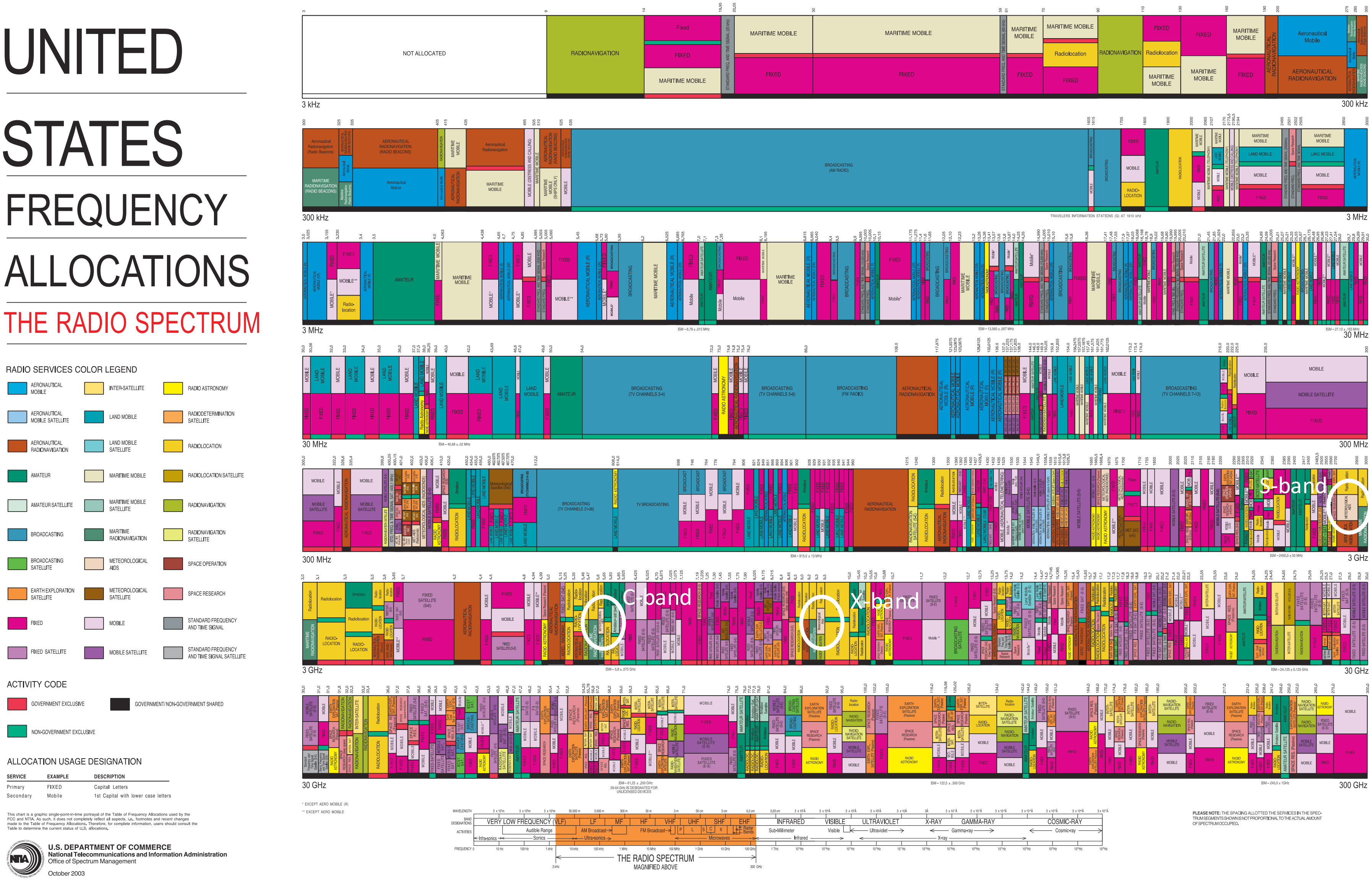
The Electromagnetic Spectrum in Earth's Atmosphere

<u>Main topics</u>

- Types of EM Radiation
- Radio frequency spectrum

Electromagnetic spectrum



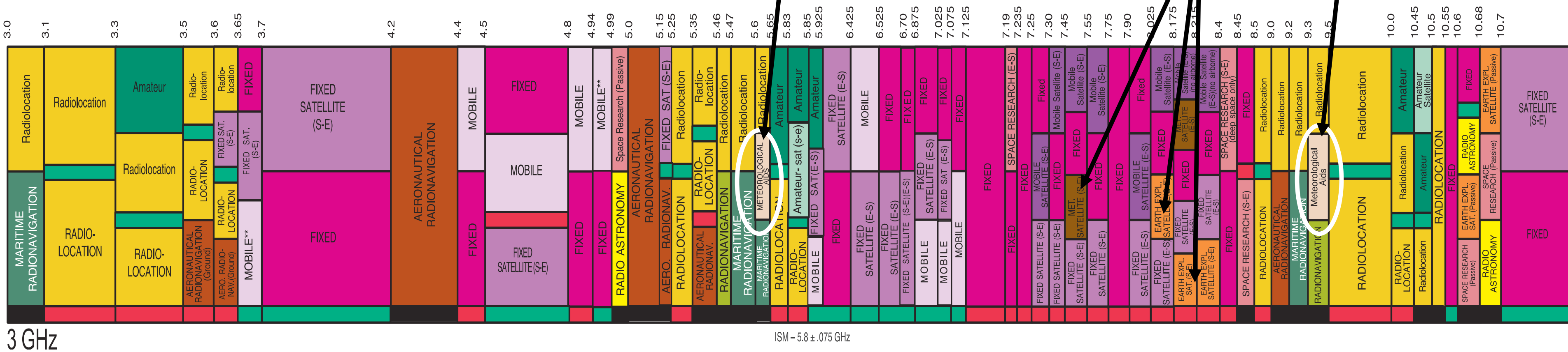


Full table: https://transition.fcc.gov/oet/spectrum/table/fcctable.pdf

Other meteorological/earth exploration satellites

C-band

X-band



Full table: https://transition.fcc.gov/oet/spectrum/table/fcctable.pdf

MR3522: Remote Sensing of the Atmosphere and Ocean

Absorption and Scattering in the Atmosphere

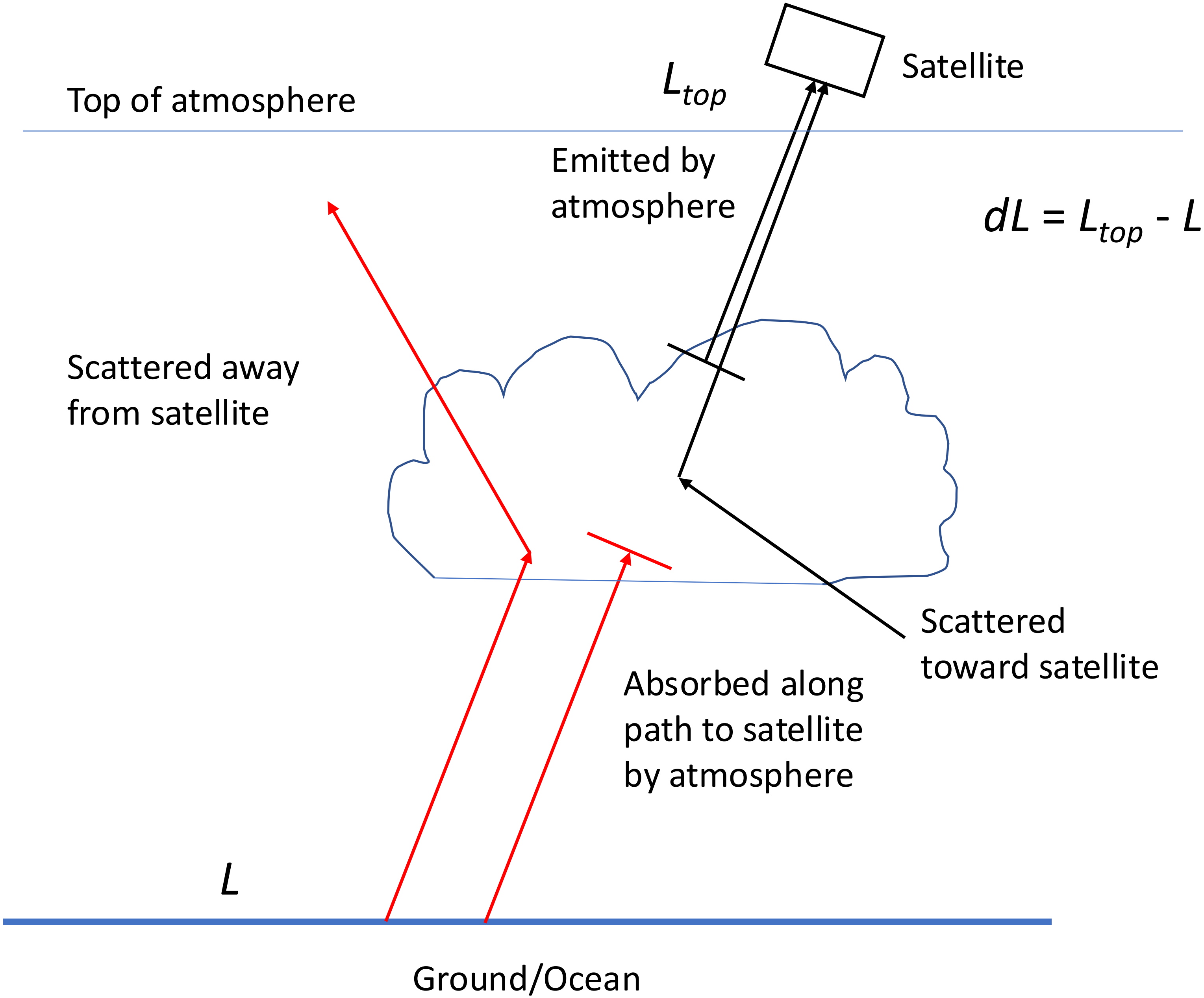
<u>Main Topics</u>

- Transmissivity of atmosphere
- Absorption wavelengths
- Atmospheric windows
- Scattering properties of atmosphere

What do satellite instruments measure?
Radiance at some frequency/wavelength at the **top of the atmosphere** (TOA)

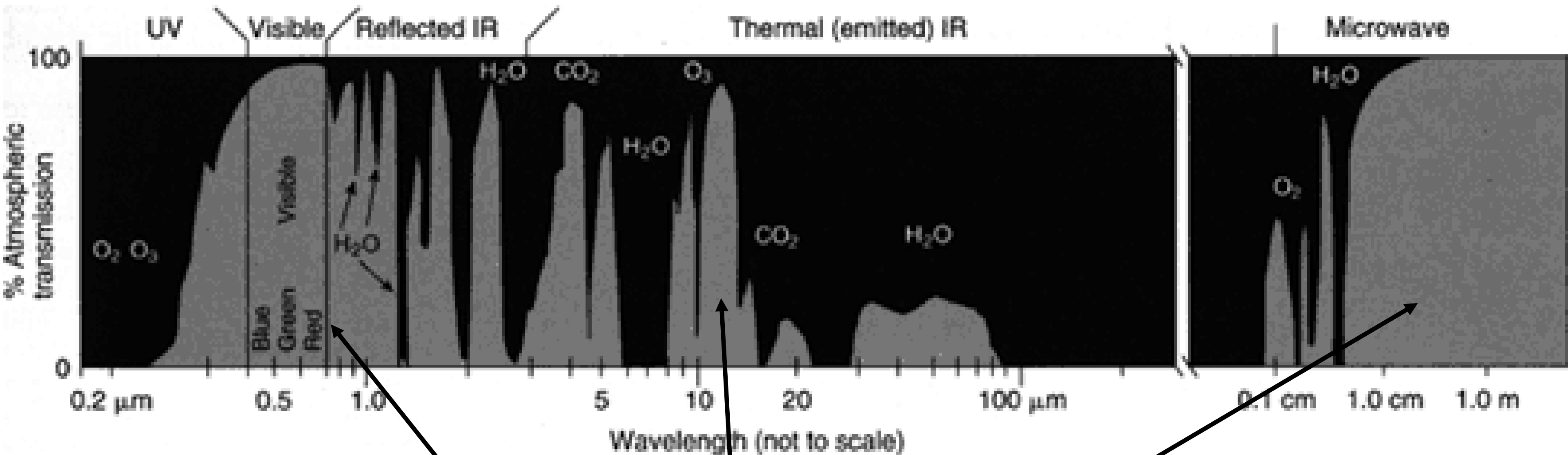
What are the sources of observed radiation?
Scattering and **Emission**

What prevents radiation from reaching the top of the atmosphere? **Scattering and Absorption**



Satellite
L_{top}
Top of atmosphere
Emitted by
atmosphere
$dL = L_{top} - L$
Scattered away
from satellite
Scattered
toward satellite
Absorbed along
path to satellite
by atmosphere
L
Ground/Ocean

Atmospheric Transmission Spectra

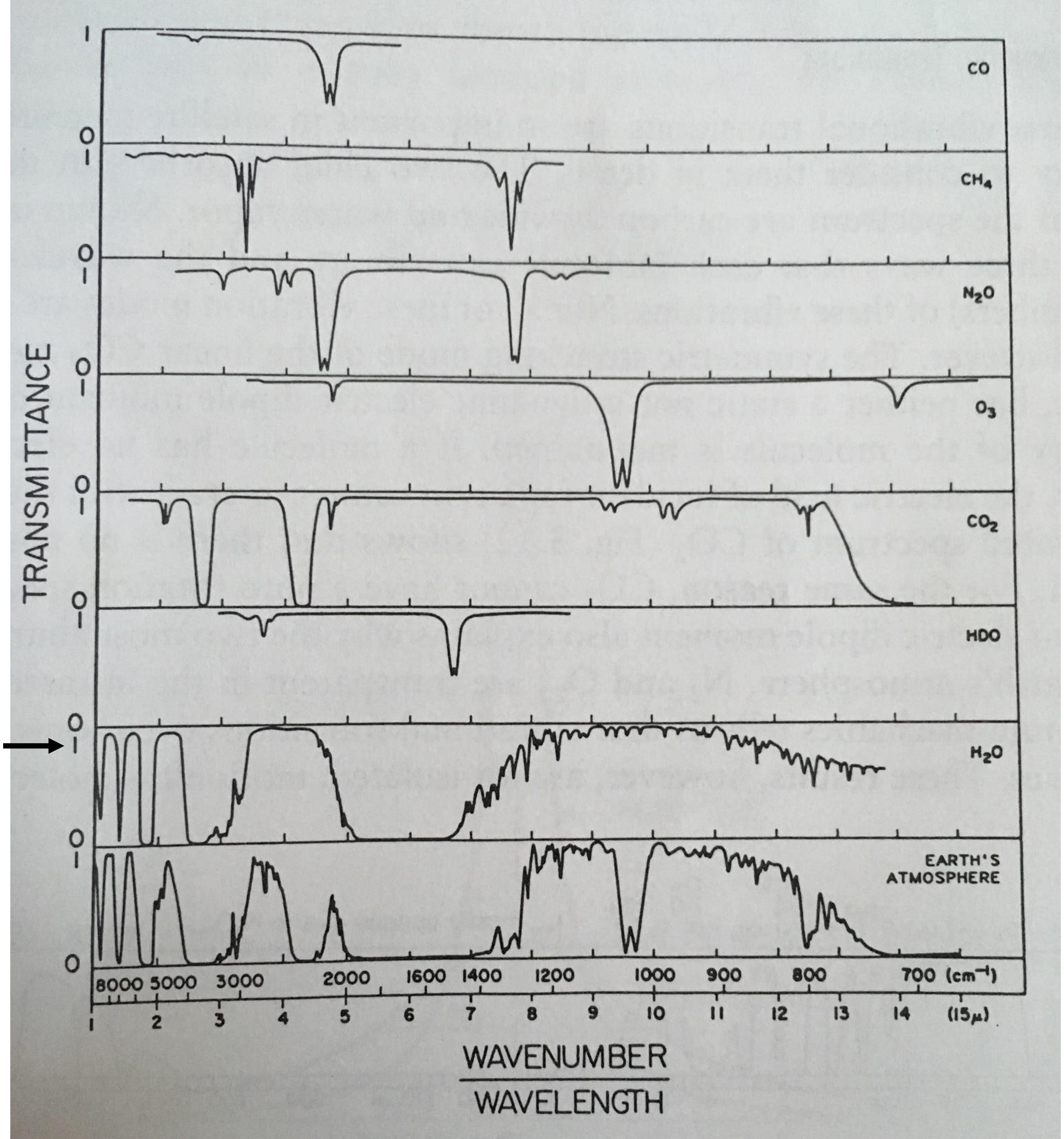


NASA

Atmospheric "windows"

Transmission spectra for common absorbing atmospheric constituents in IR

Transmittance of 1 means no radiation is absorbed or scattered by the molecule plotted. This varies by wavelength.



Carbon monoxide

Methane

Nitrous oxide

Ozone

Carbon dioxide

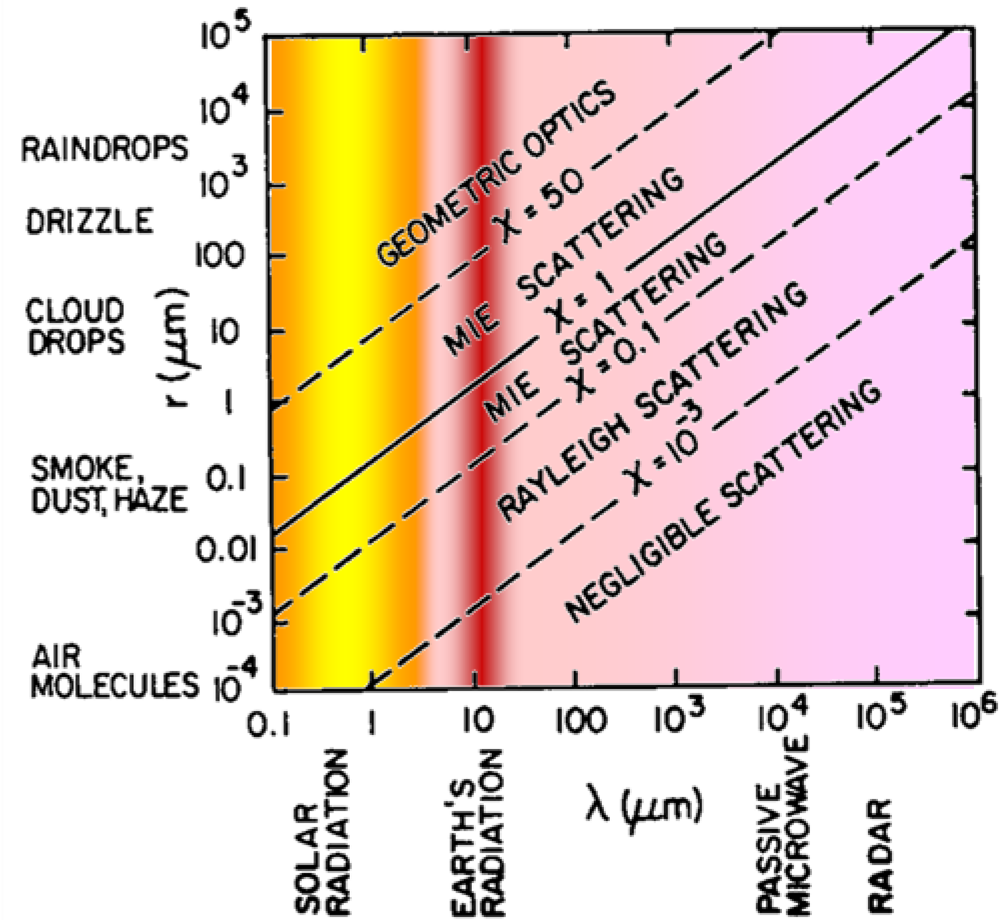
Semi-heavy water vapor

Water vapor

Total

Scattering in Earth's Atmosphere

(size parameter $\chi = 2\pi r/\lambda$)



MR3522: Remote Sensing of the Atmosphere and Ocean

Planck's Law and Wien's Law

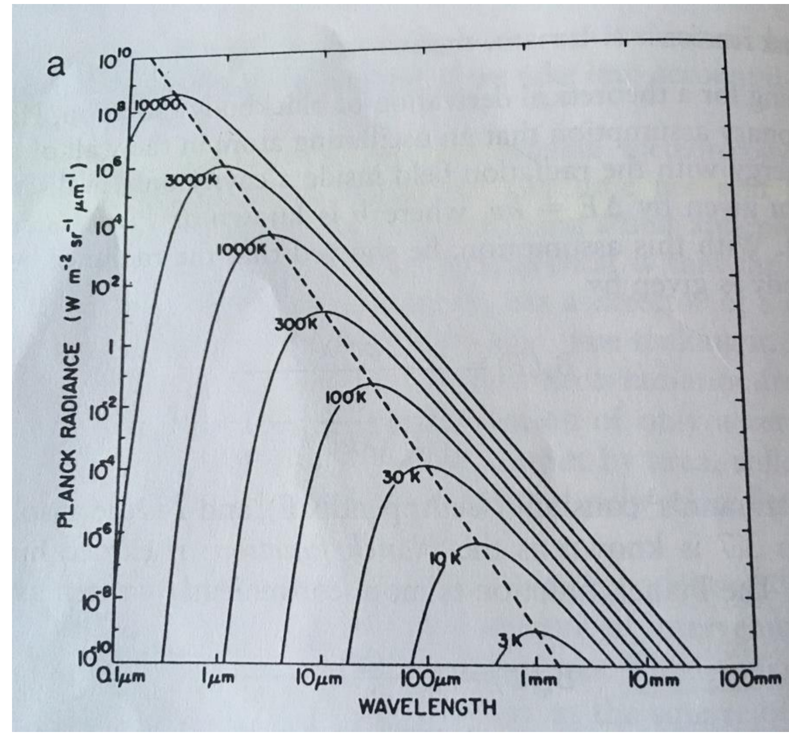
Main Topics

- Planck's Law
- Wien's Law
- Planck emission curves
- Discrepancies between Planck irradiance and observed irradiance caused by absorption and scattering

Most radiation we observe for remote sensing of Earth is either emitted by the Sun or objects in Earth's atmosphere or on/near Earth's surface.

Planck function: $B_\lambda(T) = \frac{2\hbar c^2 \lambda^{-5}}{e^{\frac{\hbar c}{\lambda k T}} - 1}$

$k = 1.38 \times 10^{-23}$ m^2 kg s^{-2} K^{-1}
$\hbar = 6.62607004 \times 10^{-34}$ m^2 kg s^{-1}
c = 3 x 10^8 m s^{-1}



Wien's Law: $\lambda_m T = 2897.9\ \mu m\ K$

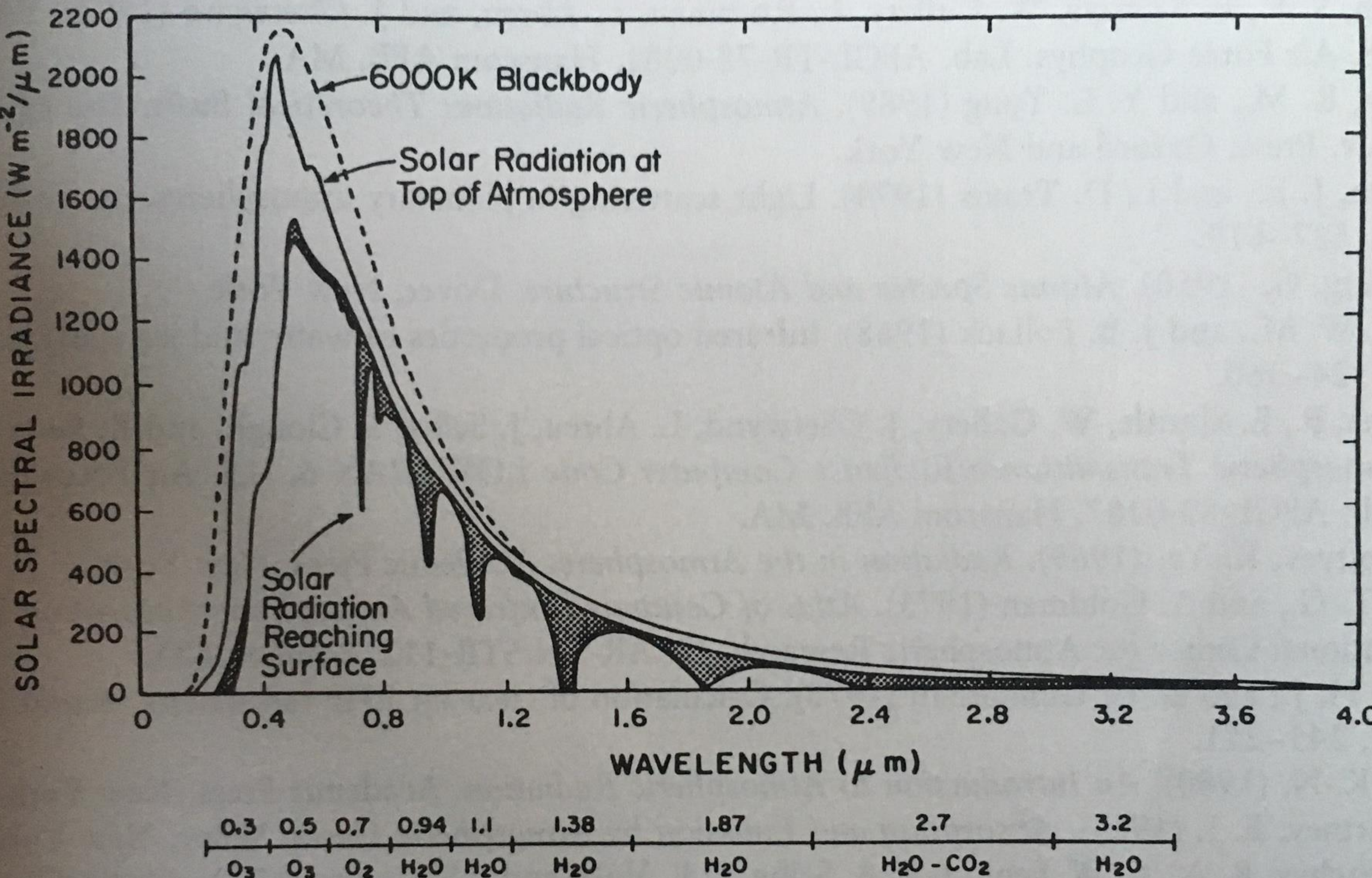


FIGURE 3.23. Solar spectral irradiance. The dashed curve shows the approximate irradiance that would be received at the Earth if the sun were a 6000-K blackbody. The top solid curve shows the spectral irradiance at the top of the atmosphere. (The integral under this curve is the solar constant.) The bottom solid curve represents the approximate solar irradiance reaching the Earth's surface after absorption and scattering in the atmosphere. The shaded area represents absorption by atmospheric gases, and the difference between the top solid curve and the envelope of the shaded area represents scattering. [Adapted from Liou (1980). Reprinted by permission of Academic Press.]

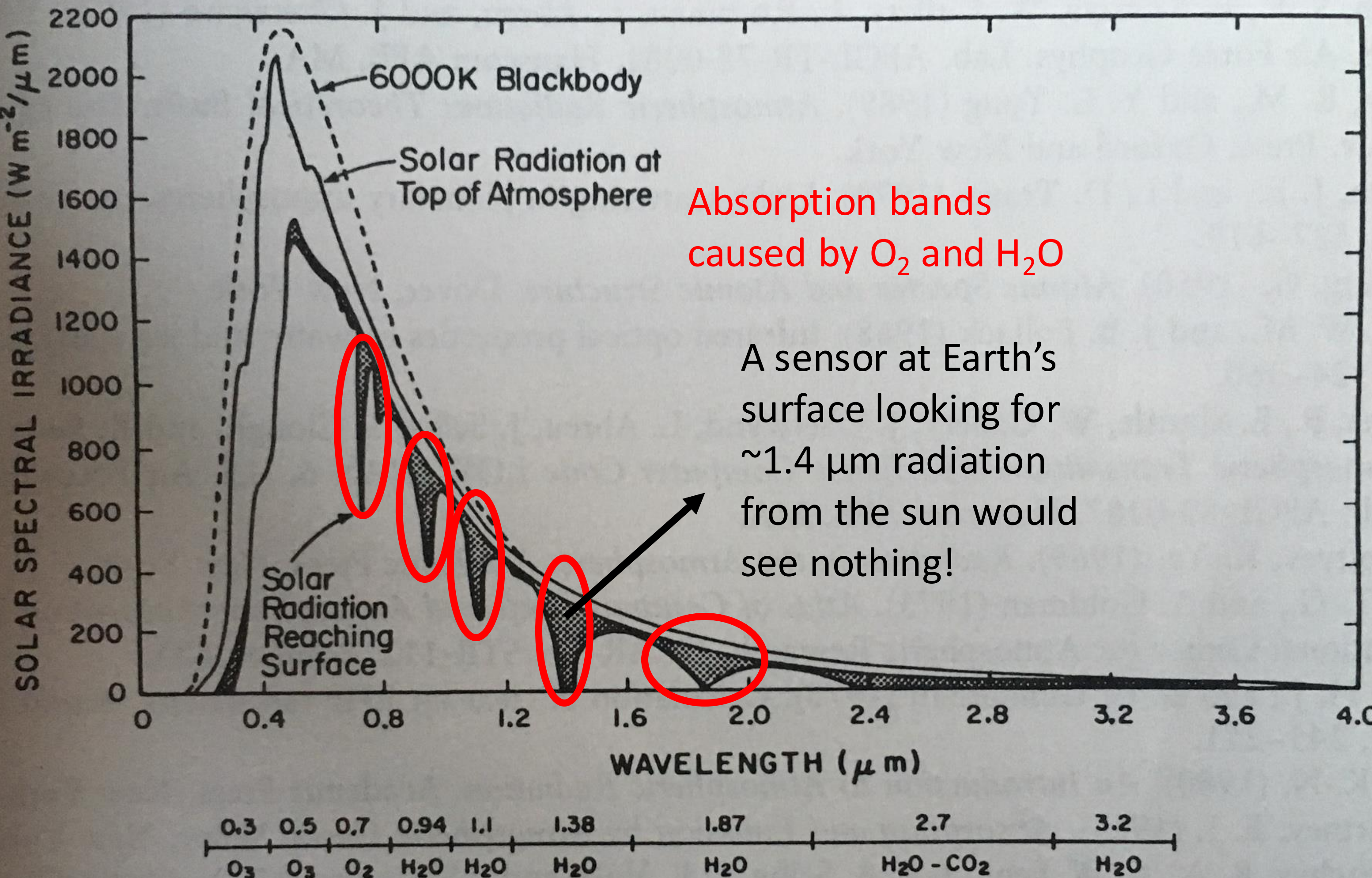


FIGURE 3.23. Solar spectral irradiance. The dashed curve shows the approximate irradiance that would be received at the Earth if the sun were a 6000-K blackbody. The top solid curve shows the spectral irradiance at the top of the atmosphere. (The integral under this curve is the solar constant.) The bottom solid curve represents the approximate solar irradiance reaching the Earth's surface after absorption and scattering in the atmosphere. The shaded area represents absorption by atmospheric gases, and the difference between the top solid curve and the envelope of the shaded area represents scattering. [Adapted from Liou (1980). Reprinted by permission of Academic Press.]

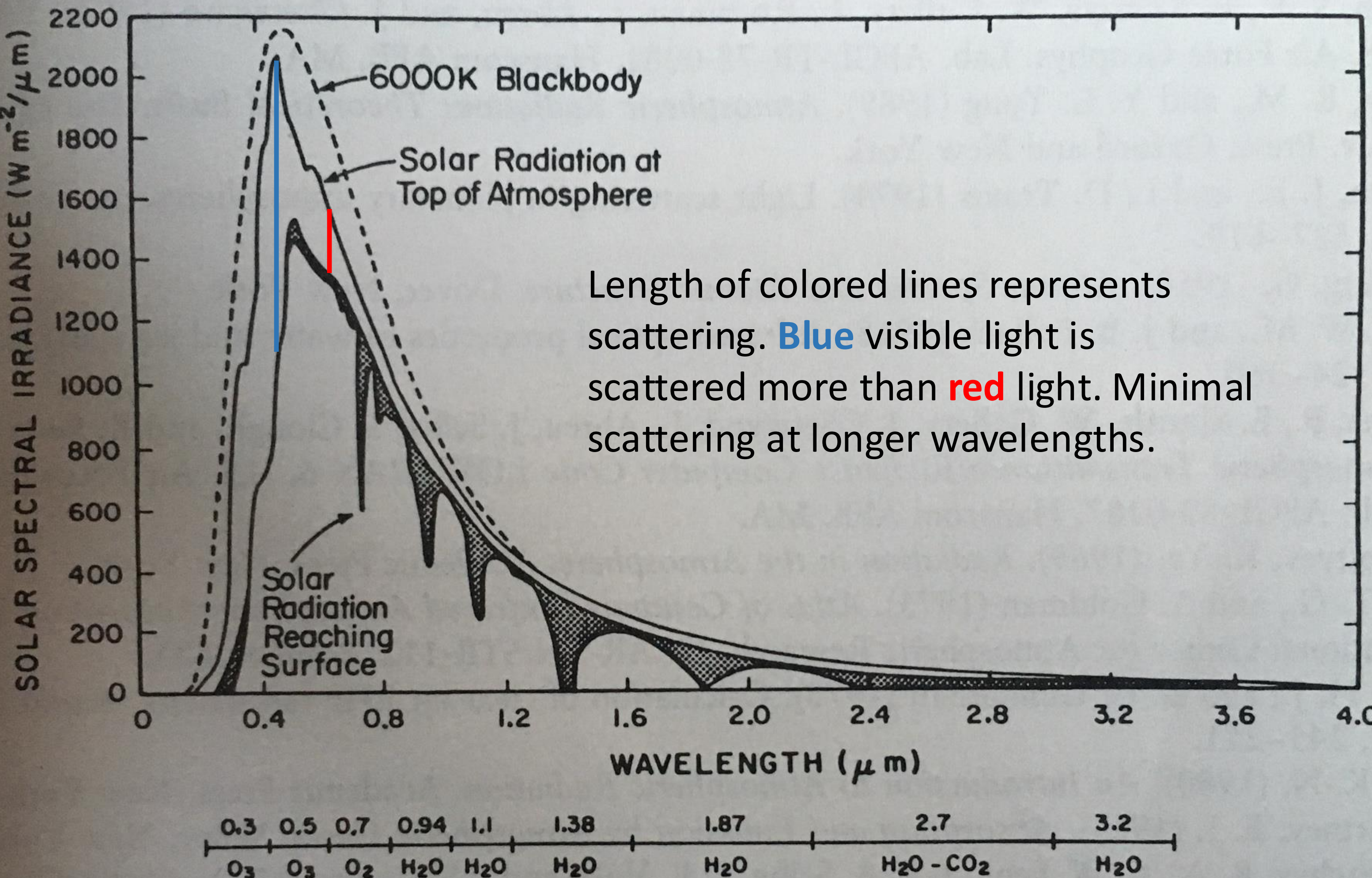
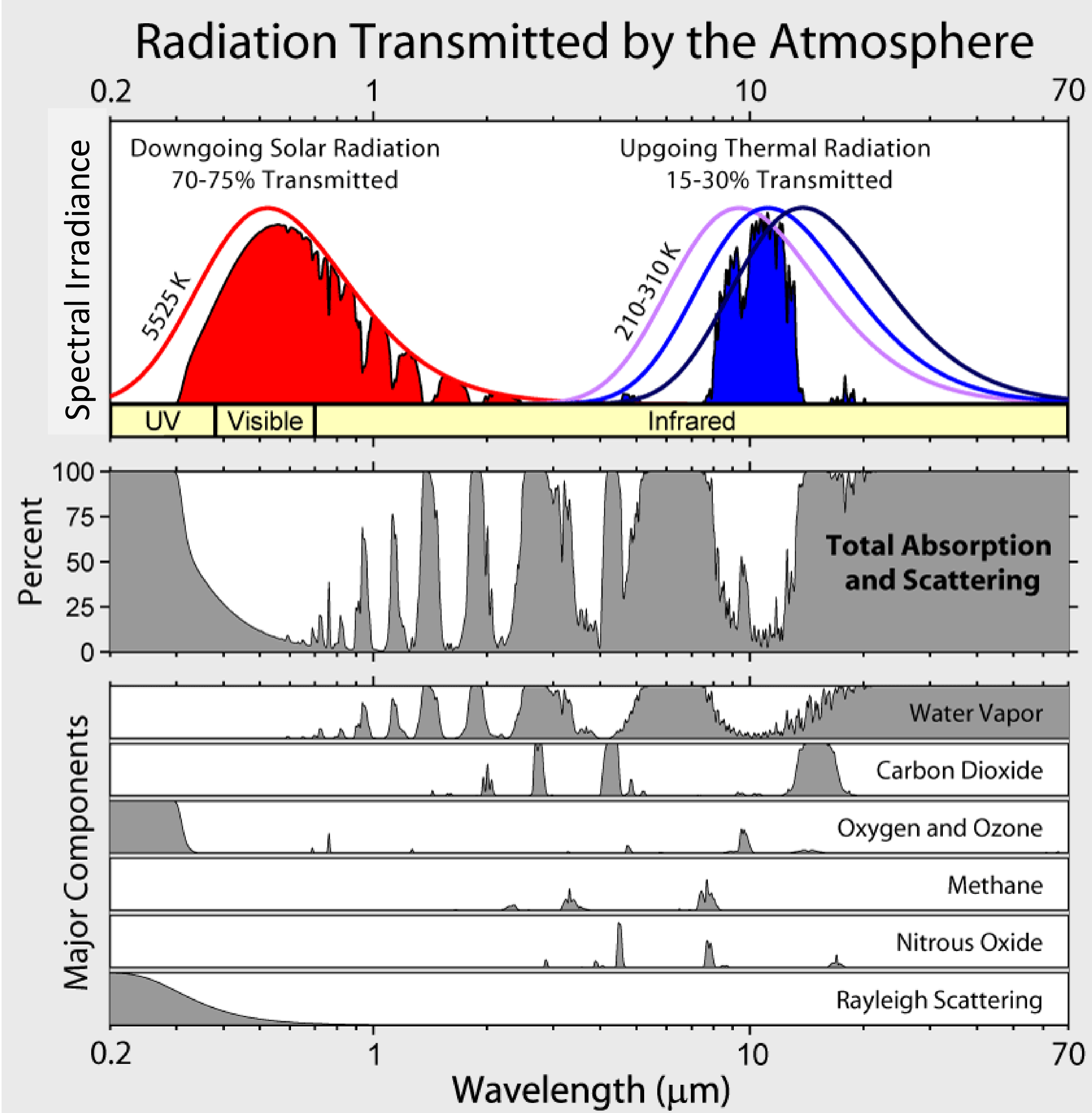


FIGURE 3.23. Solar spectral irradiance. The dashed curve shows the approximate irradiance that would be received at the Earth if the sun were a 6000-K blackbody. The top solid curve shows the spectral irradiance at the top of the atmosphere. (The integral under this curve is the solar constant.) The bottom solid curve represents the approximate solar irradiance reaching the Earth's surface after absorption and scattering in the atmosphere. The shaded area represents absorption by atmospheric gases, and the difference between the top solid curve and the envelope of the shaded area represents scattering. [Adapted from Liou (1980). Reprinted by permission of Academic Press.]



Credit: Robert Rohde

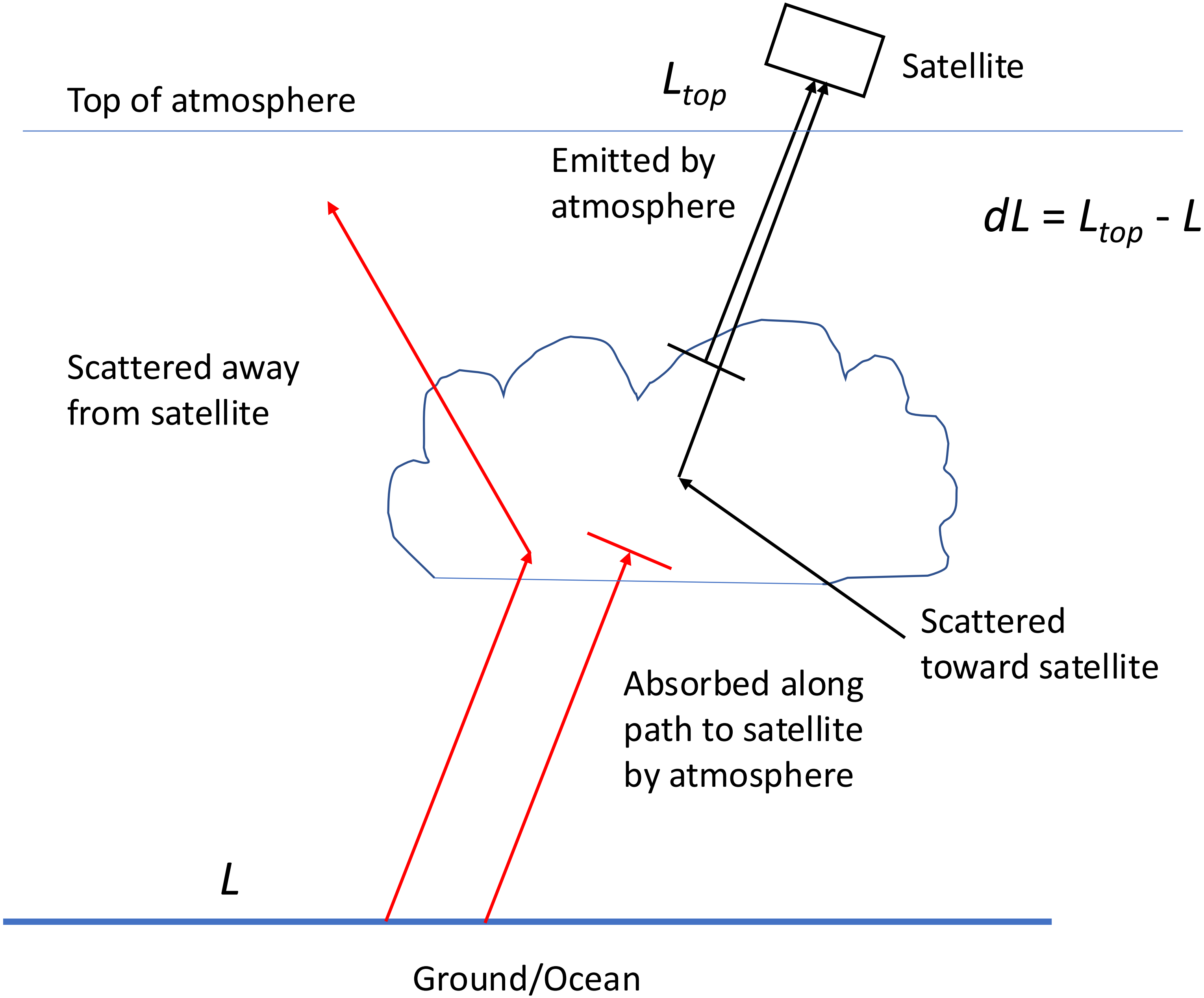
MR3522: Remote Sensing of the Atmosphere and Ocean

Mathematical Expressions of Radiative Extinction

<u>Main Topics</u>

- Schwarzchild's Equation
- Direct transmissivity
- Optical depth

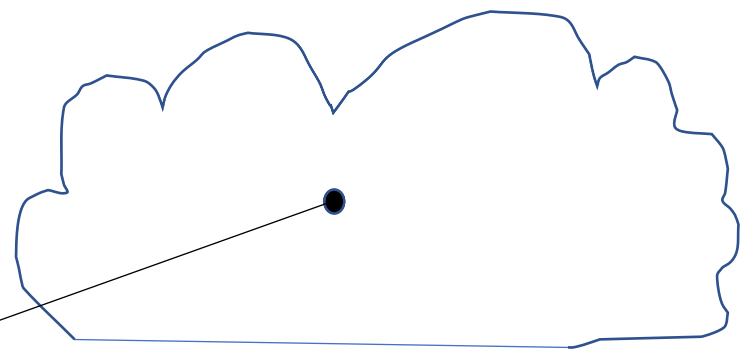
Module 1.4


Top of atmosphere
L_{top}
Satellite
Emitted by atmosphere
$dL = L_{top} - L$
Scattered away from satellite
Scattered toward satellite
Absorbed along path to satellite by atmosphere
L
Ground/Ocean

Top of atmosphere

L_{top} Satellite

$dL = L_{top} - L$



At this point X, and along a path **r** toward the satellite:

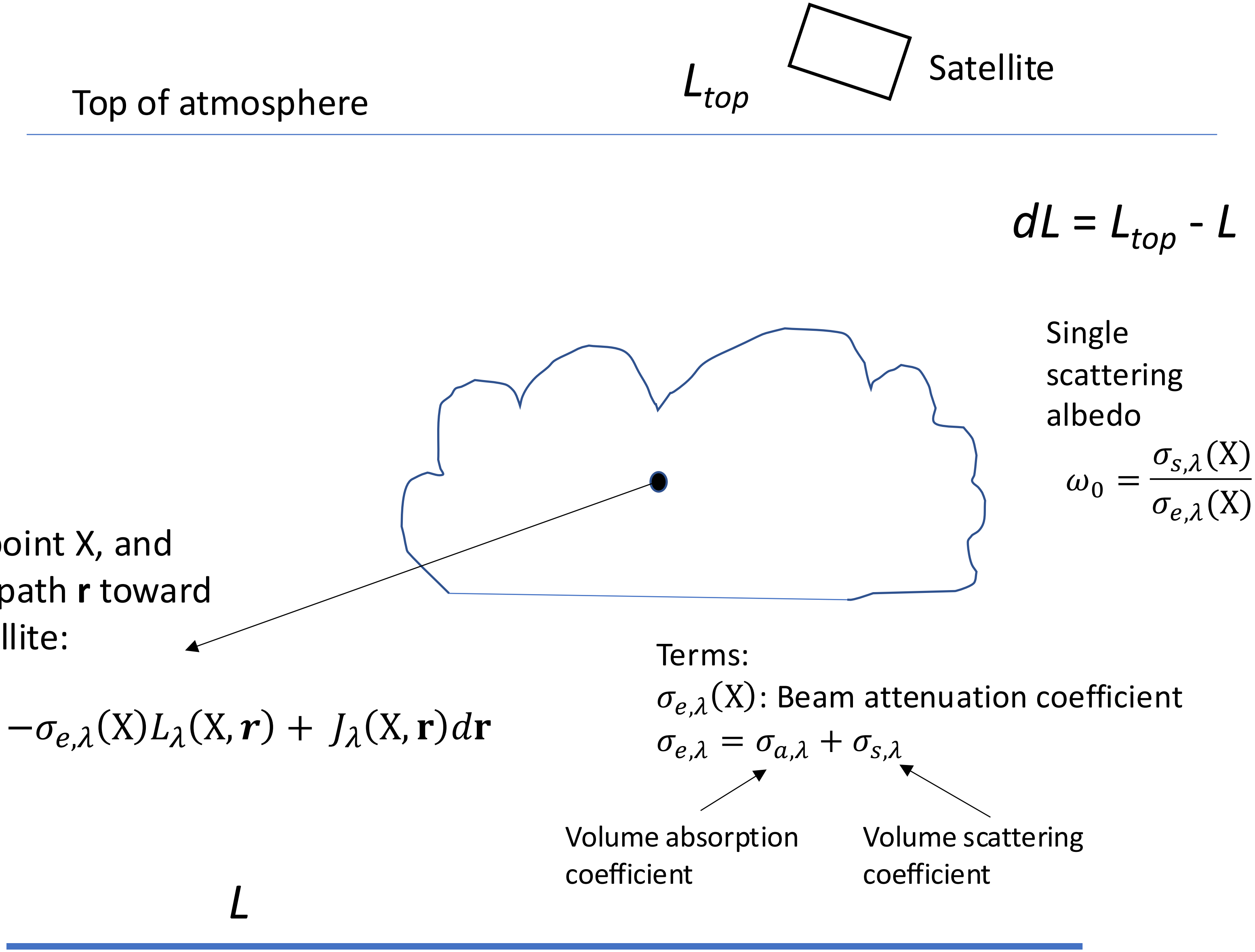
$$dL(\mathrm{X}, \mathbf{r}) = -A - B + C + D$$

Two terms for sources (C, D) and two terms for sinks (A, B)

$$dL(\mathrm{X}, \mathbf{r}) = -\sigma_{e,\lambda}(\mathrm{X}) L_{\lambda}(\mathrm{X}, \boldsymbol{r}) + J_{\lambda}(\mathrm{X}, \mathbf{r}) d\mathbf{r}$$

L

Ground/Ocean



Top of atmosphere

L_{top} Satellite

$dL = L_{top} - L$

Single scattering albedo

$$\omega_0 = \frac{\sigma_{s,\lambda}(\mathrm{X})}{\sigma_{e,\lambda}(\mathrm{X})}$$

At this point X, and along a path **r** toward the satellite:

$$dL(\mathrm{X}, \mathbf{r}) = -\sigma_{e,\lambda}(\mathrm{X}) L_\lambda(\mathrm{X}, \boldsymbol{r}) + J_\lambda(\mathrm{X}, \mathbf{r}) d\mathbf{r}$$

Terms:

$\sigma_{e,\lambda}(\mathrm{X})$: Beam attenuation coefficient

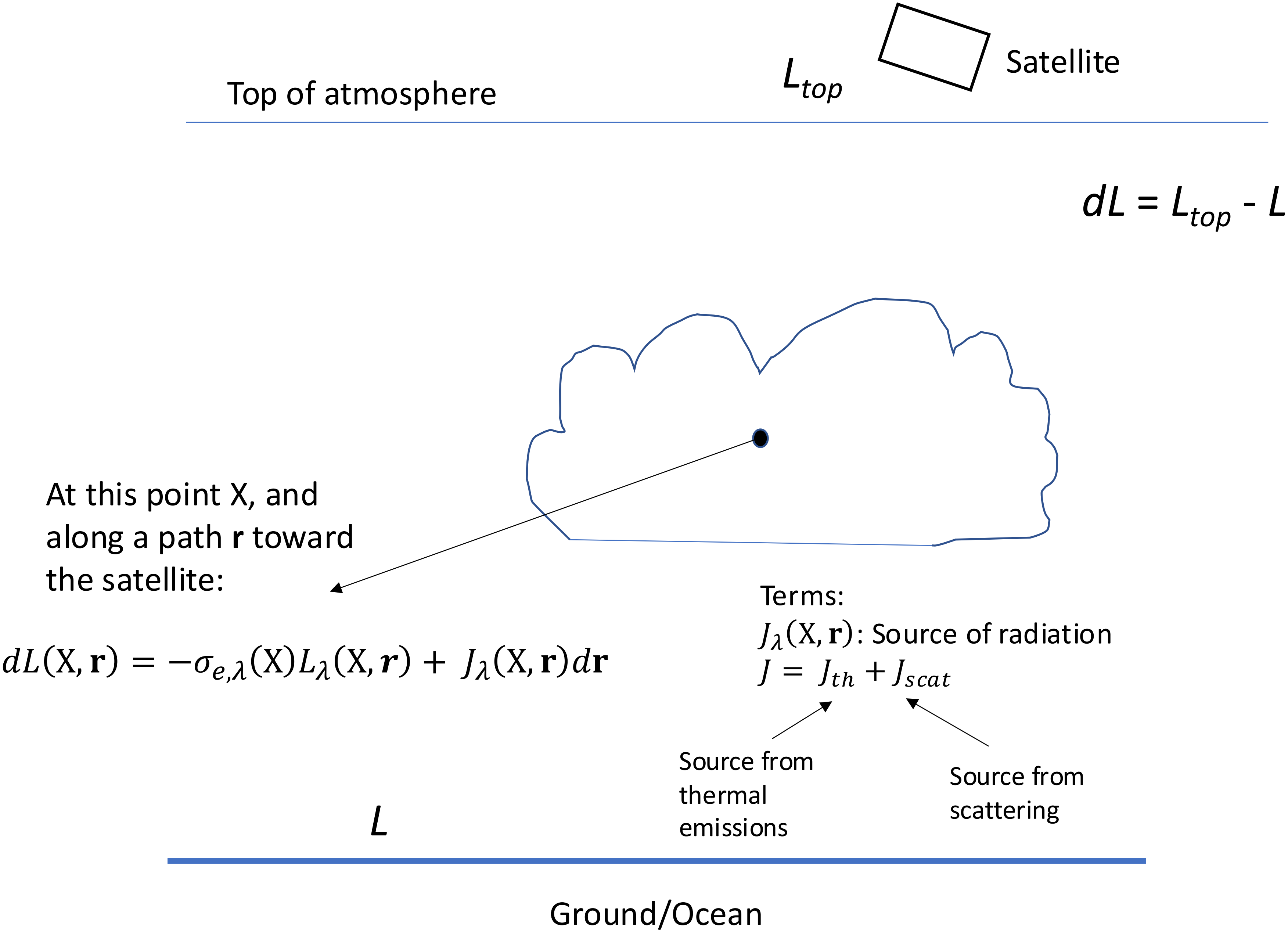
$\sigma_{e,\lambda} = \sigma_{a,\lambda} + \sigma_{s,\lambda}$

Volume absorption coefficient

Volume scattering coefficient

L

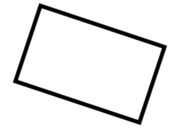
Ground/Ocean



Top of atmosphere
L_{top}
Satellite
$dL = L_{top} - L$
At this point X, and along a path **r** toward the satellite:
$dL(\mathrm{X},\mathbf{r}) = -\sigma_{e,\lambda}(\mathrm{X}) L_\lambda(\mathrm{X},\boldsymbol{r}) + J_\lambda(\mathrm{X},\mathbf{r})d\mathbf{r}$
Terms:
$J_\lambda(\mathrm{X},\mathbf{r})$: Source of radiation
$J = J_{th} + J_{scat}$
Source from thermal emissions
Source from scattering
L
Ground/Ocean

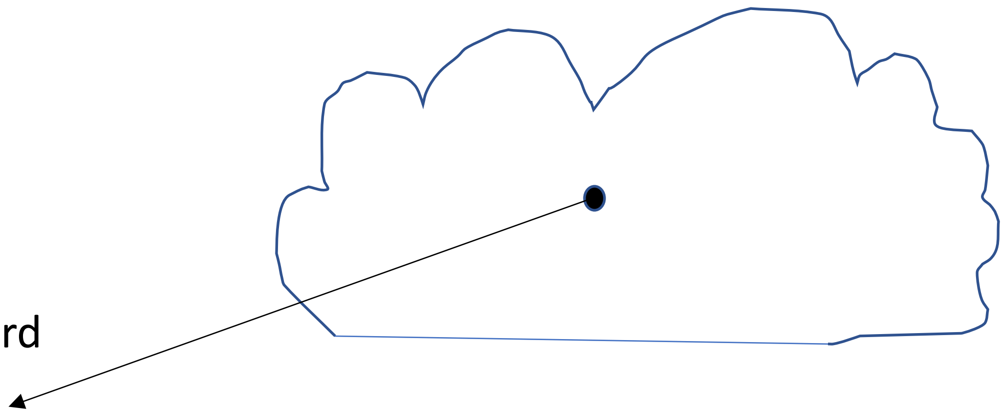
Top of atmosphere

L_{top}



Satellite

$dL = L_{top} - L$



At this point X, and along a path **r** toward the satellite:

$$dL(\mathrm{X}, \mathbf{r}) = -\sigma_{e,\lambda}(\mathrm{X}) L_{\lambda}(\mathrm{X}, \boldsymbol{r}) + J_{\lambda}(\mathrm{X}, \mathbf{r}) d\mathbf{r}$$

$$J = J_{th} + J_{scat}$$

$$J_{th}(\lambda, \mathrm{X}) = \sigma_{a,\lambda} B_{\lambda}(T(\mathrm{X}))$$

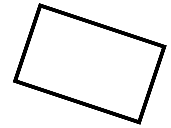
Recall Kirchhoff's Law*: $|\sigma_{a,\lambda}| = \varepsilon_{\lambda}$

L

Ground/Ocean

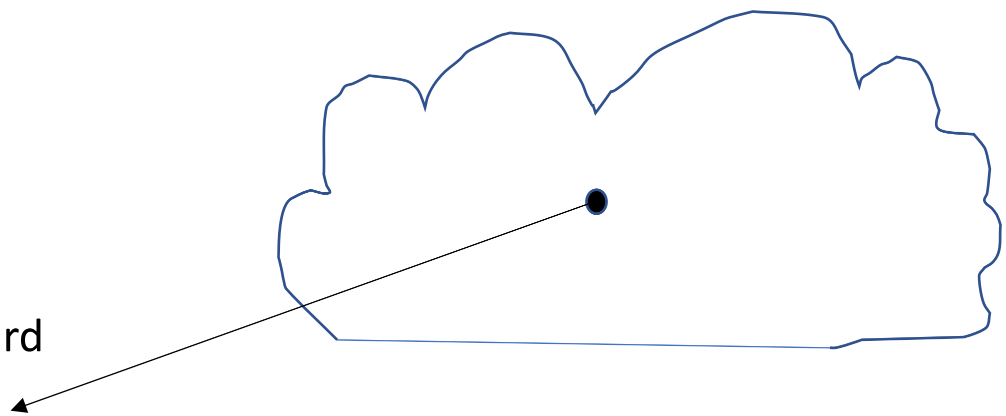
Top of atmosphere

L_{top}



Satellite

$dL = L_{top} - L$



At this point X, and along a path **r** toward the satellite:

$$dL(\mathrm{X},\mathbf{r}) = -\sigma_{e,\lambda}(\mathrm{X})L_{\lambda}(\mathrm{X},\boldsymbol{r}) + J_{\lambda}(\mathrm{X},\mathbf{r})d\mathbf{r}$$

$$J = J_{th} + J_{scat}$$

$$J_{scat}(\lambda,\mathrm{X}) = \int_{4\pi} \gamma_{s,\square}(\boldsymbol{r},\boldsymbol{r}',\boldsymbol{X})\, L_{\lambda}(\boldsymbol{r}',\boldsymbol{X})d\Omega'$$

$\gamma_{s,\lambda}$(**r**,**r**′,**X**) = volume scattering function
(Probability per distance that a photon moving in a direction **r**′ will be scattered into the direction **r**)

L

Ground/Ocean

Optical Depth and Direct Transmittance

Optical depth is unitless; it does not represent an actual physical depth! It is sometimes called optical thickness.

Normal or *vertical path* optical depth (δ):

$$\delta_\lambda(z) = \int_z^\infty \sigma_{e,\lambda}(z')dz'$$

This is the same as the optical depth of the atmosphere if integrated from 0 to ∞.

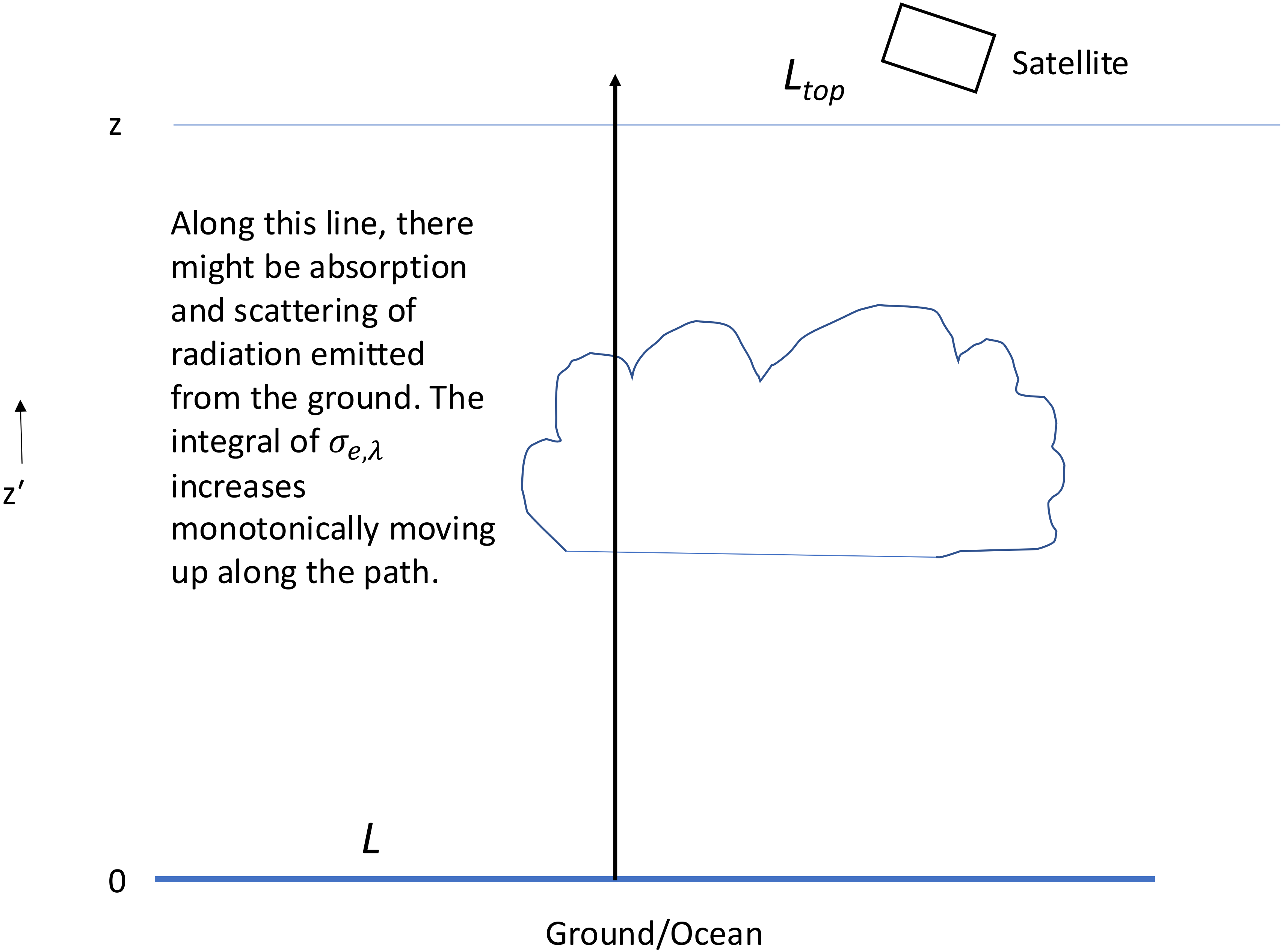
Direct transmittance:

$$\tau_d = e^{-\delta_\lambda(z')/\mu}$$

$$\mu = \cos\theta$$

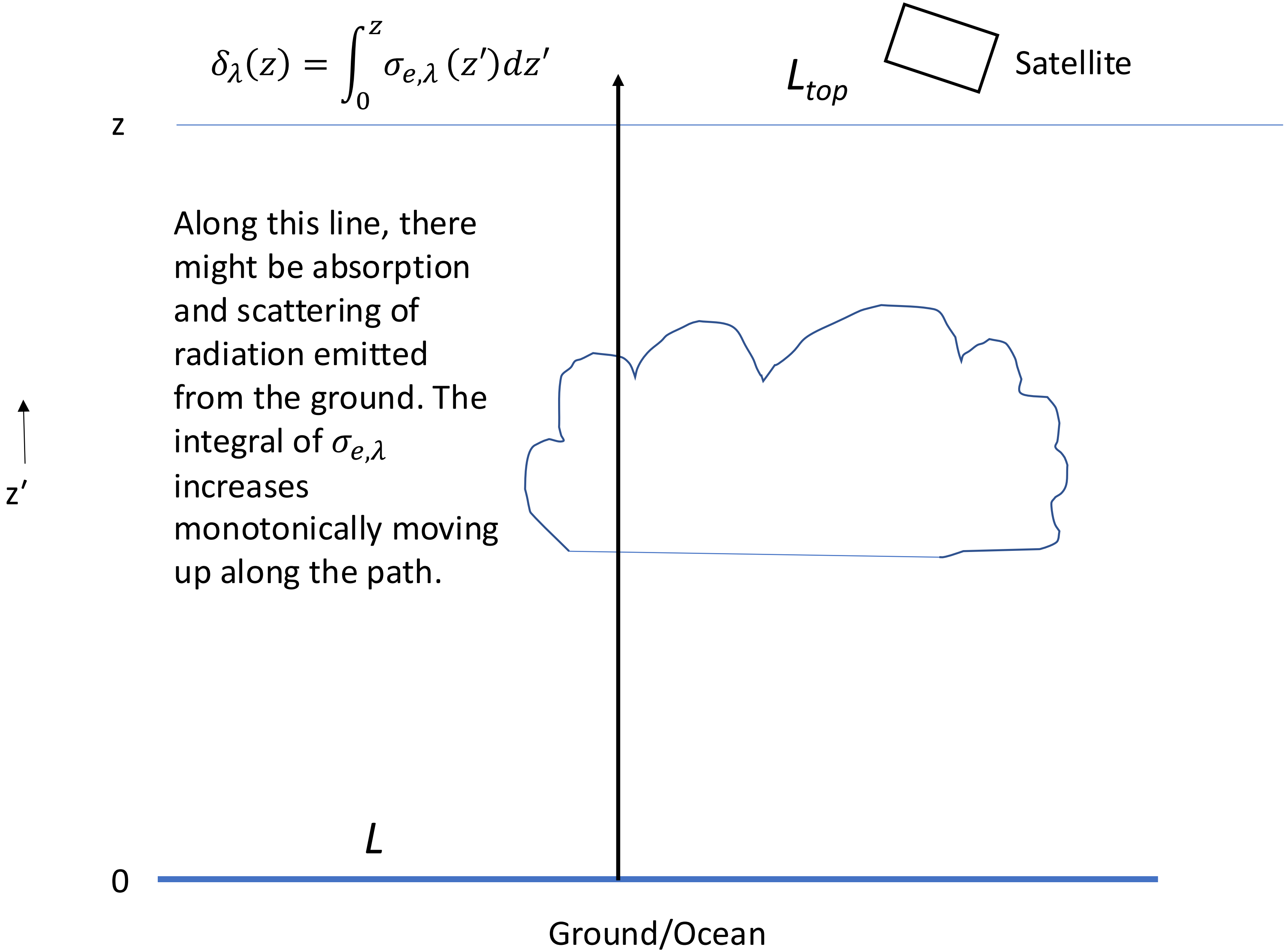
θ is the slant path angle of radiation

Path optical depth (regardless of whether the path is vertical) is then $\delta_\lambda(s) = \int_{s_1}^{s_2} \sigma_{e,\lambda}(s')ds'$ in which s' is the coordinate along the path (which is just z' if the path is vertical).



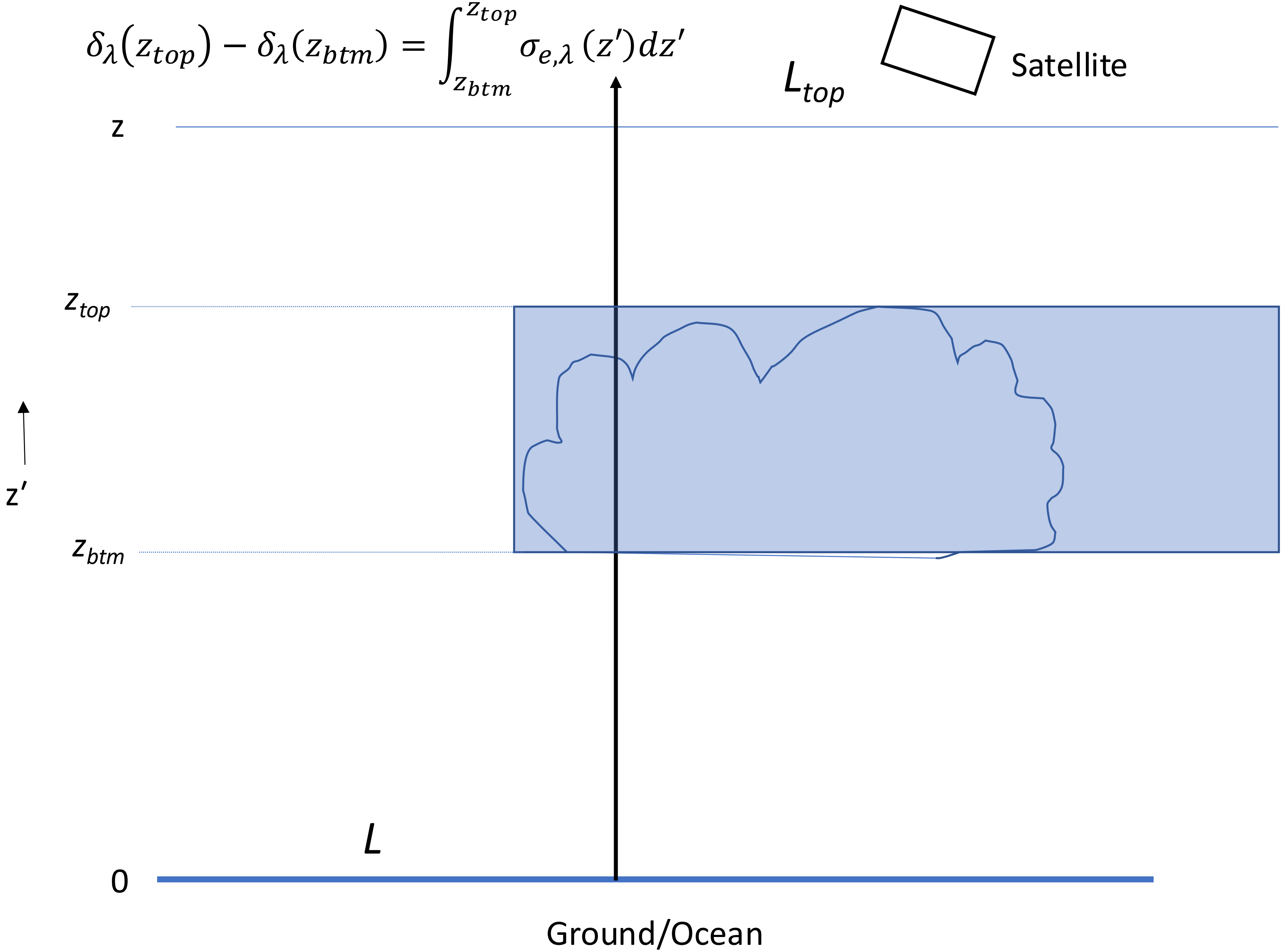
Along this line, there might be absorption and scattering of radiation emitted from the ground. The integral of $\sigma_{e,\lambda}$ increases monotonically moving up along the path.

$$\delta_\lambda(z) = \int_0^z \sigma_{e,\lambda}(z')dz'$$

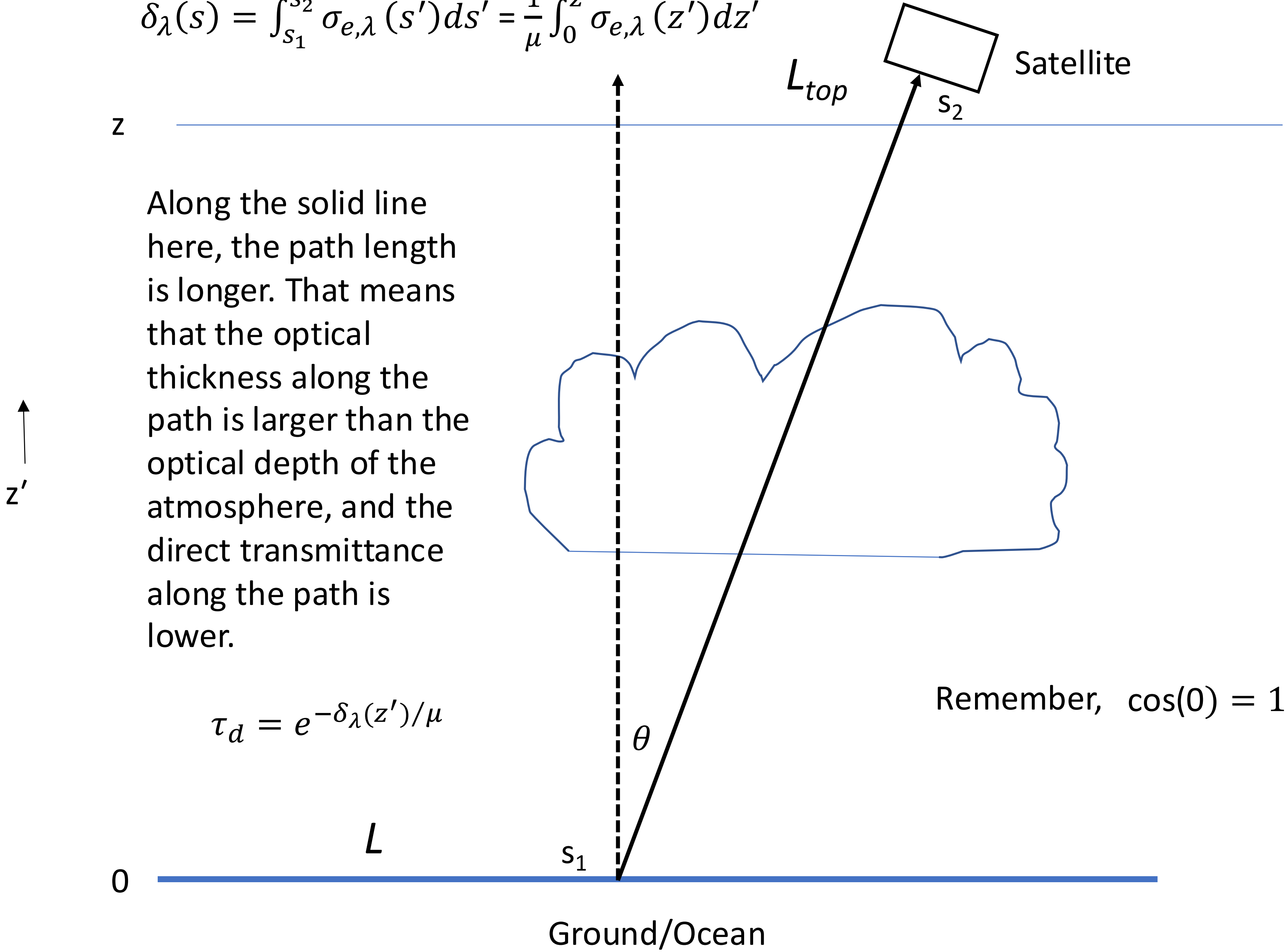


Along this line, there might be absorption and scattering of radiation emitted from the ground. The integral of $\sigma_{e,\lambda}$ increases monotonically moving up along the path.

$$\delta_\lambda(z_{top}) - \delta_\lambda(z_{btm}) = \int_{z_{btm}}^{z_{top}} \sigma_{e,\lambda}(z')dz'$$



$$\delta_\lambda(s) = \int_{s_1}^{s_2} \sigma_{e,\lambda}(s')ds' = \frac{1}{\mu}\int_0^z \sigma_{e,\lambda}(z')dz'$$



Along the solid line here, the path length is longer. That means that the optical thickness along the path is larger than the optical depth of the atmosphere, and the direct transmittance along the path is lower.

$$\tau_d = e^{-\delta_\lambda(z')/\mu}$$

Remember, $\cos(0) = 1$

MR3522: Remote Sensing of the Atmosphere and Ocean

Idealized Expressions of Radiative Transfer

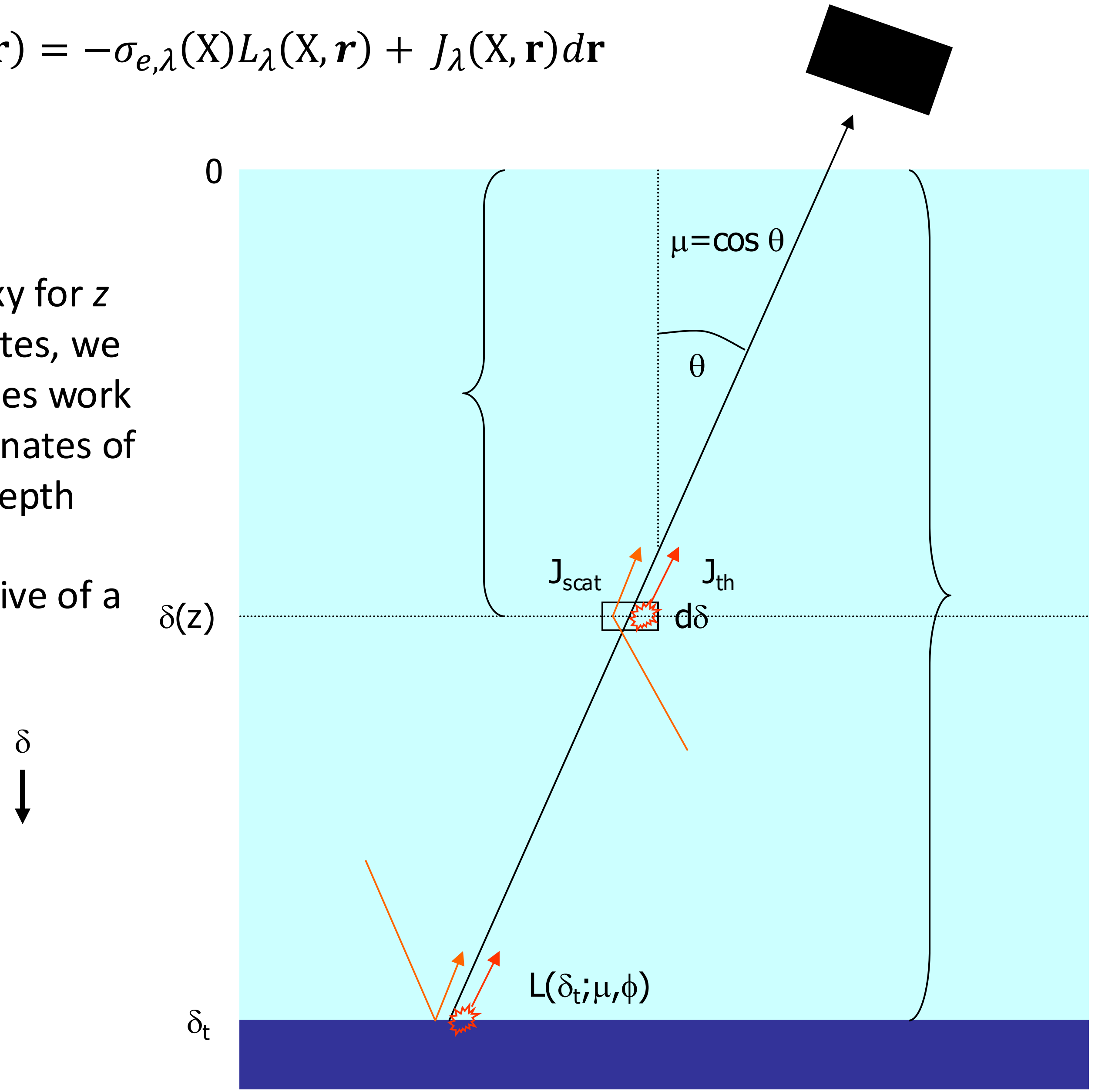
Main Topics

- Beer's Law
- Idealized cases of Schwarzchild's equation

$$dL(\mathrm{X},\mathbf{r}) = -\sigma_{e,\lambda}(\mathrm{X})L_\lambda(\mathrm{X},\boldsymbol{r}) + J_\lambda(\mathrm{X},\mathbf{r})d\mathbf{r}$$

$$dL(\mathrm{X},\mathbf{r}) = -\sigma_{e,\lambda}(\mathrm{X})L_\lambda(\mathrm{X},\boldsymbol{r}) + J_\lambda(\mathrm{X},\mathbf{r})d\mathbf{r}$$

As a proxy for *z* coordinates, we sometimes work in coordinates of optical depth from the perspective of a satellite.



The path through the atmosphere is longer than a vertical path, so the path optical depth is larger than the optical depth of the atmosphere.

$$\delta_\lambda(s) = \frac{\delta_\lambda(z)}{\mu}$$

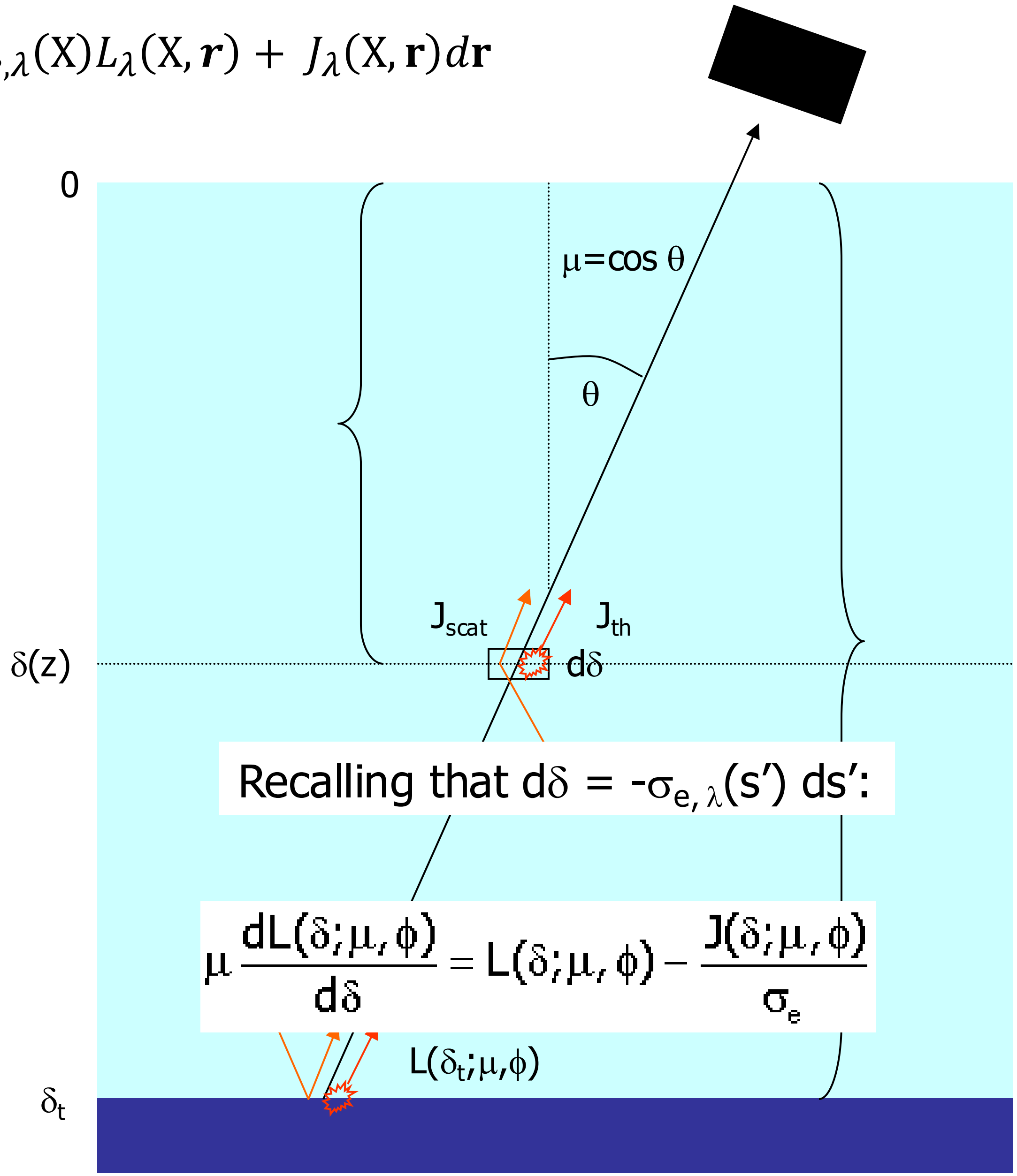
$\mu = \cos\theta$

Φ Is just the azimuthal angle, but we are working in 2D and not so worried about this.

$$dL(\mathrm{X},\mathbf{r}) = -\sigma_{e,\lambda}(\mathrm{X})L_\lambda(\mathrm{X},\boldsymbol{r}) + J_\lambda(\mathrm{X},\mathbf{r})d\mathbf{r}$$

As a proxy for *z* coordinates, we sometimes work in coordinates of optical depth from the perspective of a satellite.

δ ↓



The path through the atmosphere is longer than a vertical path, so the path optical depth is larger than the optical depth of the atmosphere.

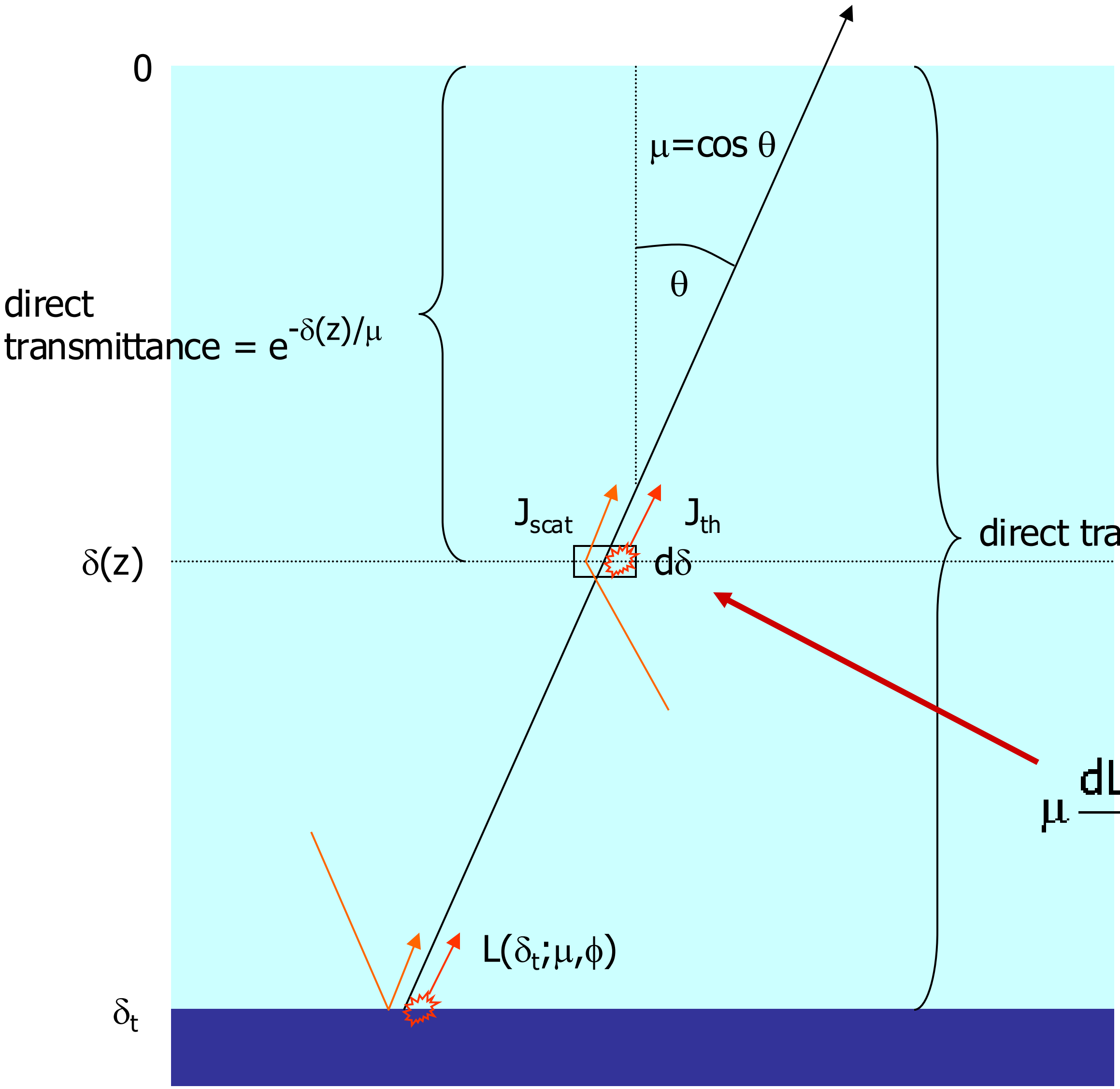
$$\delta_\lambda(s) = \frac{\delta_\lambda(z)}{\mu}$$

$$\mu = \cos\theta$$

Φ Is just the azimuthal angle, but we are working in 2D and not so worried about this.

General solution at top of atmosphere:

$$L(0;\mu,\phi) = L(\delta_t;\mu,\phi)e^{-\delta_t/\mu} + \int_0^{\delta_t} \frac{J(\delta';\mu,\phi)}{\sigma_e(\delta')} e^{-\delta'/\mu} \frac{d\delta'}{\mu}$$



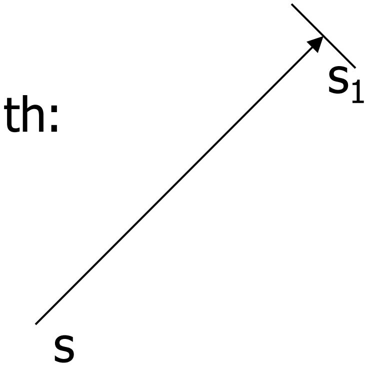
summing all changes along the path gives…

radiance change at height z

$$\mu \frac{dL(\delta;\mu,\phi)}{d\delta} = L(\delta;\mu,\phi) - \frac{J(\delta;\mu,\phi)}{\sigma_e}$$

Beer-Lambert-Bouguer Law

Assume that no sources of radiation are possible along a path:



$$dL(\mathrm{s},\mathbf{r}) = -\sigma_{e,\lambda}(\mathrm{s})L_\lambda(\mathrm{s},\boldsymbol{r}) + \cancelto{0}{J_\lambda(\mathrm{s},\mathbf{r})}d\mathbf{r}$$

$$dL(s)/\ L(s) = -\sigma_e(s)\ ds$$

integrating… $\ln L(s_1) - \ln L(s) = -\int_s^{s_1} \sigma_e(s')ds'$

$$L(s_1) = \mathrm{L}(\mathrm{s})e^{-\int_s^{s_1} \sigma_e(s')ds'}$$

Optical depth along an arbitrary path from s to s_1: $\delta(s) = \int_s^{s_1} \sigma_e(s')ds'$

$$\boxed{L(s_1) = L(s)e^{-\delta(s)}}$$

Radiance at end of path is radiance at beginning of path multiplied by direct transmittance

$\tau_d = e^{-\delta(s)}$ is direct transmittance from s to the boundary s_1

Idealized Case #1

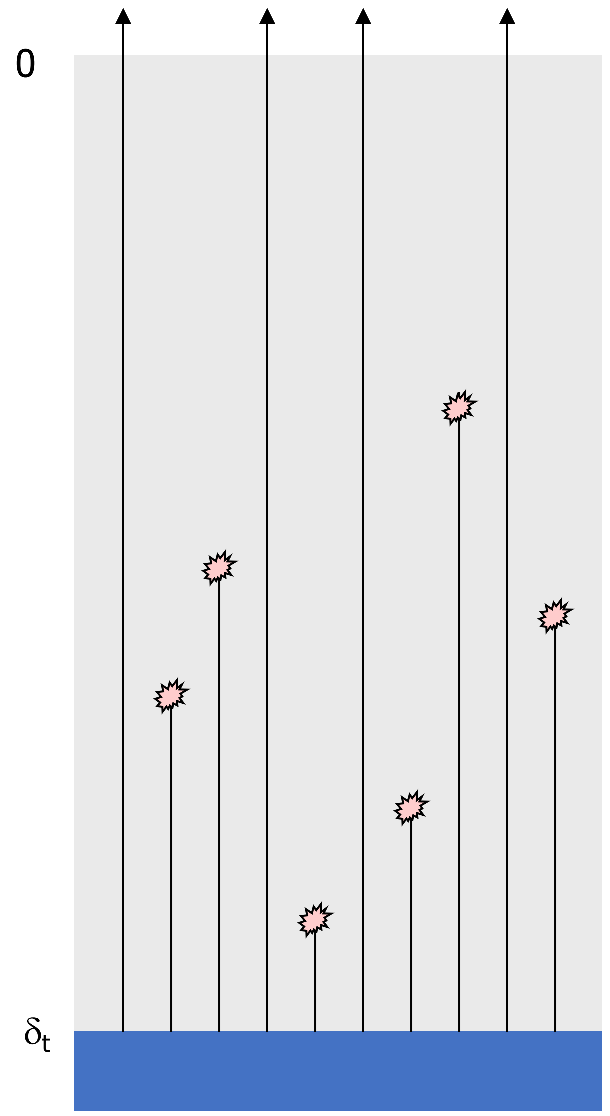
No Path Radiance

We are at a wavelength where B(λ,T) ~ 0 and there is **no scattering** into the beam

$$L(0) = L(\delta_t)e^{-\delta_t/\mu}$$

if $\theta = 0$

δ_t =	0.01	0.1	1.0	7
$e^{-\delta_t}$ =	99%	90.5%	36.8%	0.1%



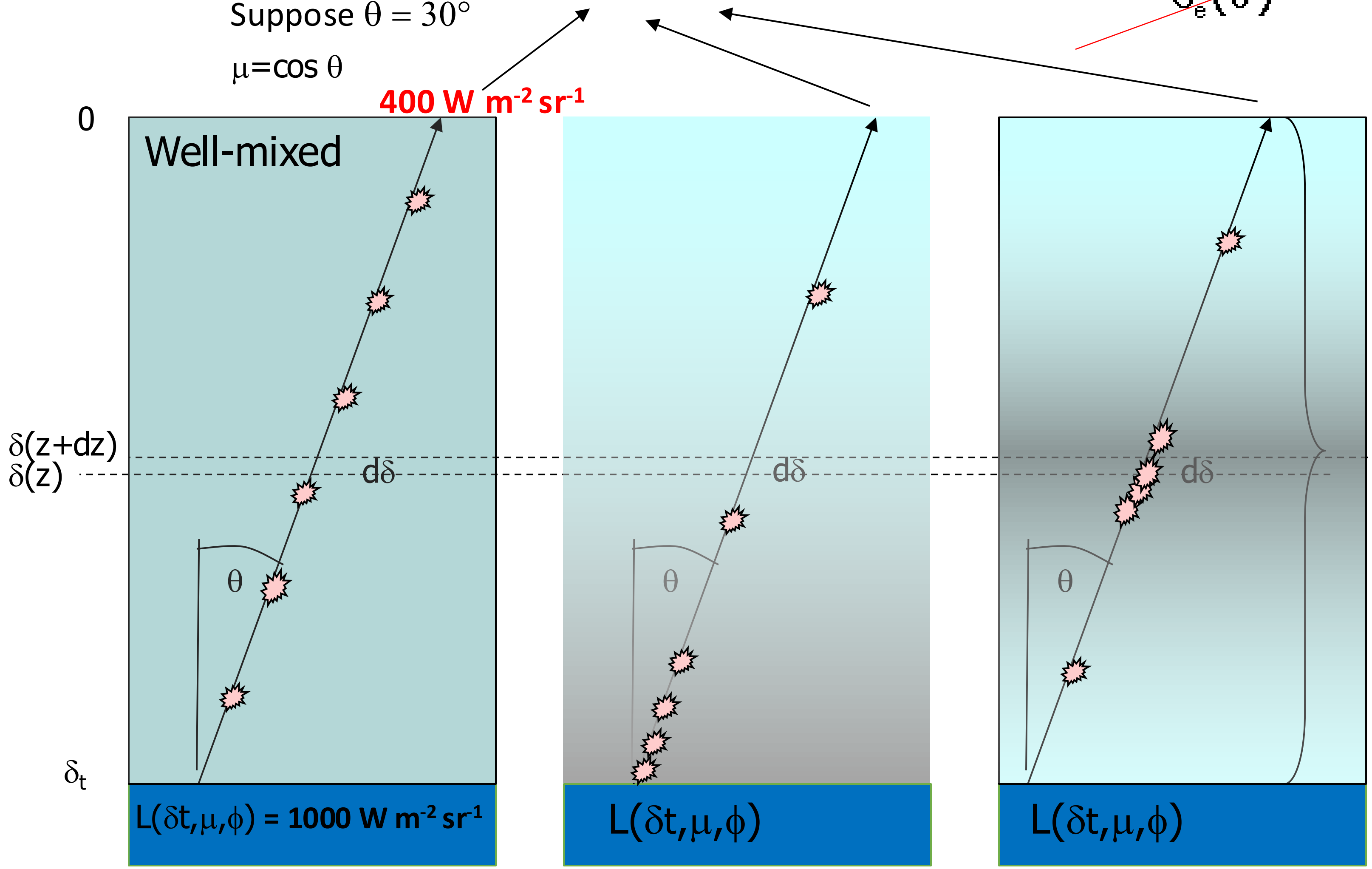
Radiance measured at the top of the atmosphere, L(0), is the same in all three

What is δ?

$$L(0;\mu,\phi) = L(\delta_t;\mu,\phi)e^{-\delta_t/\mu} + \int_0^{\delta_t} \frac{J(\delta';\mu,\phi)}{\sigma_e(\delta')} e^{-\delta'/\mu} \frac{d\delta'}{\mu} \rightarrow 0$$

Suppose $\theta = 30°$

$\mu = \cos\theta$



$$\tau_d = e^{-\delta_t/\mu}$$

Total direct transmittance can be equal in all three because it is a total along the entire view path. Variations along path subsections simply produce the same total optical depth value.

Radiance leaving the bottom of the atmosphere, L(δt), is the same in all three

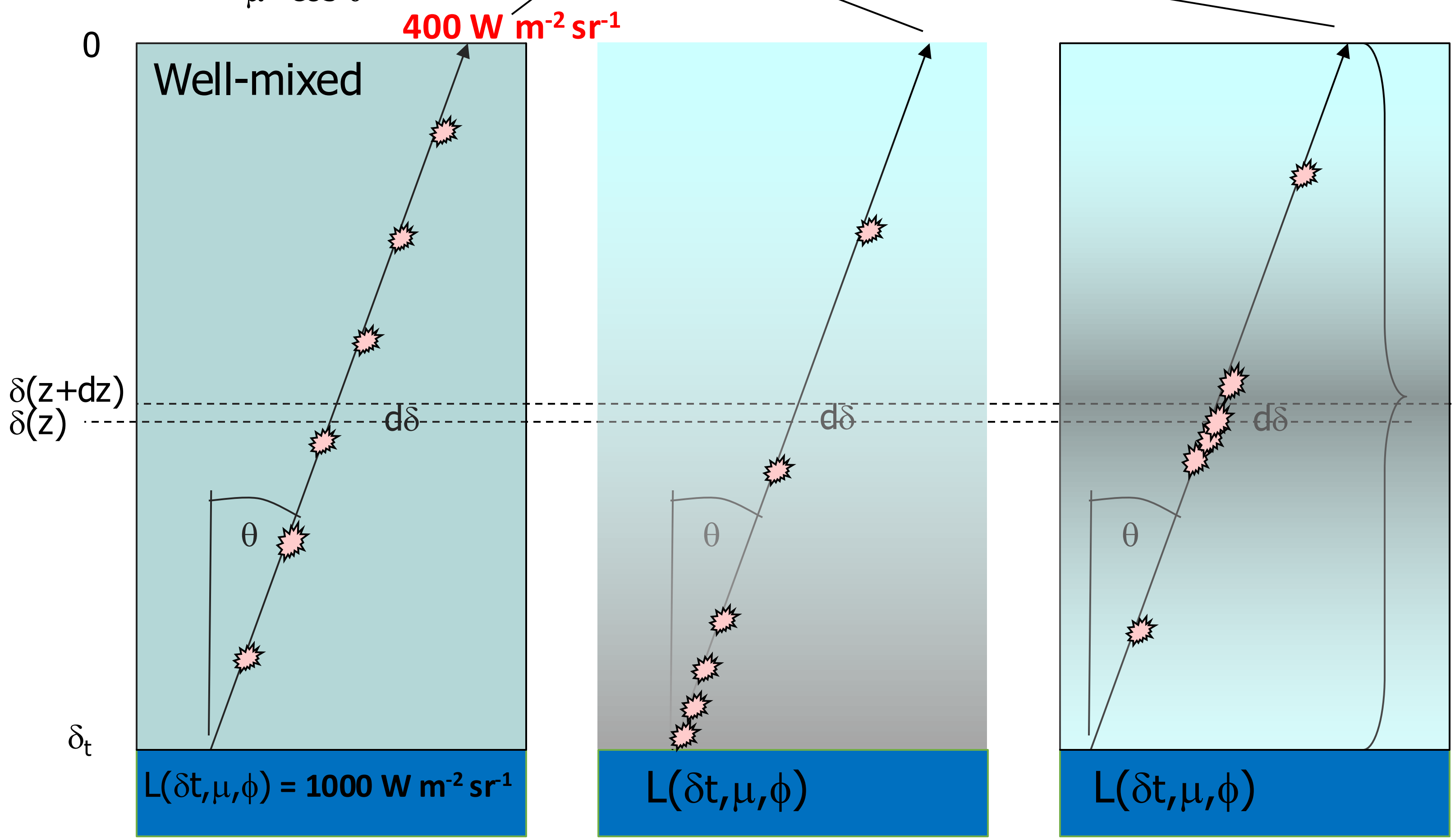
Radiance measured at the top of the atmosphere, L(0), is the same in all three

$\delta \sim 0.79$

$$L(0;\mu,\phi) = L(\delta_t;\mu,\phi)e^{-\delta_t/\mu} + \cancelto{0}{\int_0^{\delta_t} \frac{J(\delta';\mu,\phi)}{\sigma_e(\delta')} e^{-\delta'/\mu} \frac{d\delta'}{\mu}}$$

Suppose $\theta = 30°$

$\mu = \cos\theta$



$$\tau_d = e^{-\delta_t/\mu}$$

Total direct transmittance can be equal in all three because it is a total along the entire view path. Variations along path subsections simply produce the same total optical depth value.

Radiance leaving the bottom of the atmosphere, $L(\delta t)$, is the same in all three

Idealized Case #2

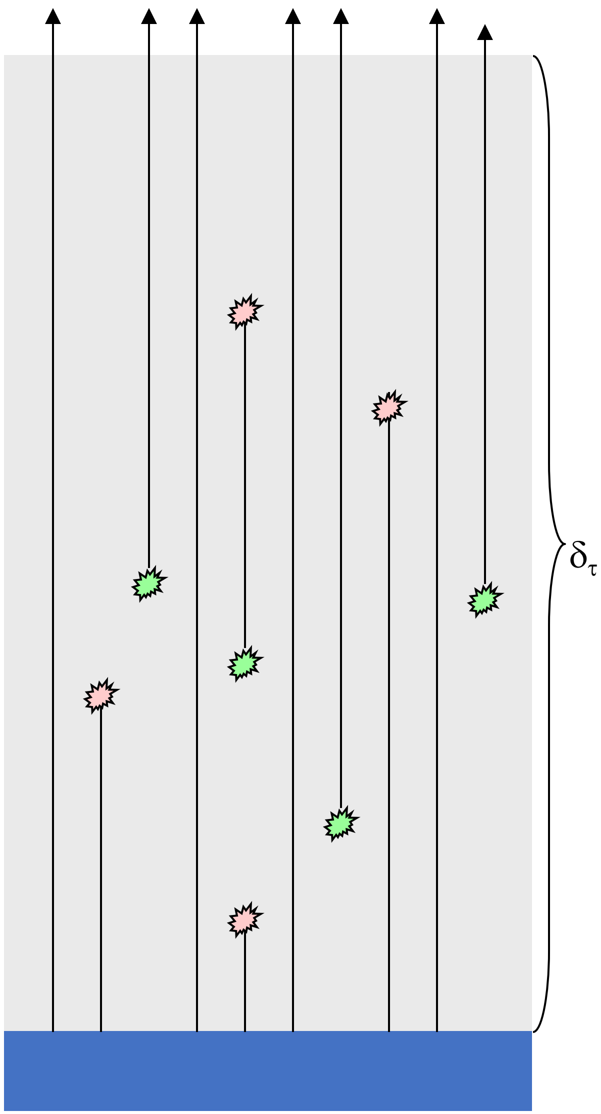
Emitted Path Radiance Only

Here emission is the only source of photons and there is **no scattering**, so $\sigma_e = \sigma_a$.

$$J_\lambda(z) = \sigma_{a,\lambda}(z)\, B_\lambda(T(z))$$

$$\varepsilon_{s,\lambda} = \sigma_{a,\lambda} \longrightarrow L(\delta_t;\mu,\phi) = \varepsilon_{s,\lambda} B_\lambda(T_s)$$

Kirchhoff's Law



Solution:

$$L(0;\mu,\phi) = L(\delta_t;\mu,\phi)e^{-\delta_t/\mu} + \int_0^{\delta_t} \frac{J(\delta';\mu,\phi)}{\sigma_e(\delta')} e^{-\delta'/\mu} \frac{d\delta'}{\mu}$$

$$L(0;\mu,\phi) = \varepsilon_{s,\lambda} B_\lambda(T_s) e^{-\delta_t/\mu} + \int_0^{\delta_t} B_\lambda(T(z)) e^{-\delta'/\mu} \frac{d\delta'}{\mu}$$

$$L(0;\mu,\phi) = \varepsilon_{s,\lambda} B_\lambda(T_s) e^{-\delta_t/\mu} + \int_0^{\delta_t} B_\lambda(T(z)) e^{-\delta'/\mu} \frac{d\delta'}{\mu}$$

Top-of-atmosphere radiance

Emitted radiance by surface

Direct transmittance across path

Emission along path

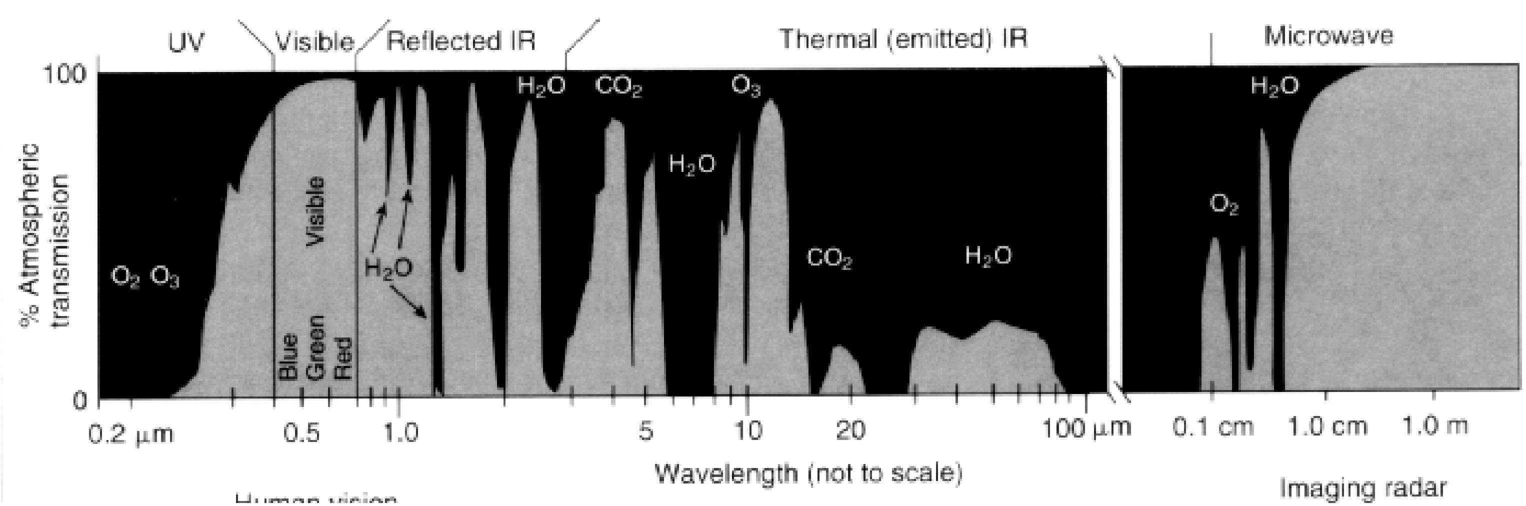
Direct transmittance along path from δ'

$$L(0;\mu,\phi) = \underbrace{\varepsilon_{s,\lambda}B_\lambda(T_s)e^{-\delta_t/\mu}}_{1} + \underbrace{\int_0^{\delta_t} B_\lambda(T(z))e^{-\delta'/\mu}\frac{d\delta'}{\mu}}_{2}$$

For which wavelengths does this solution apply?

For which wavelengths does term 1 dominate?

For which wavelengths does term 2 dominate?



Idealized Case #3

Source due to single-scattered path radiance only
(note: in general, multiple scattering is required)

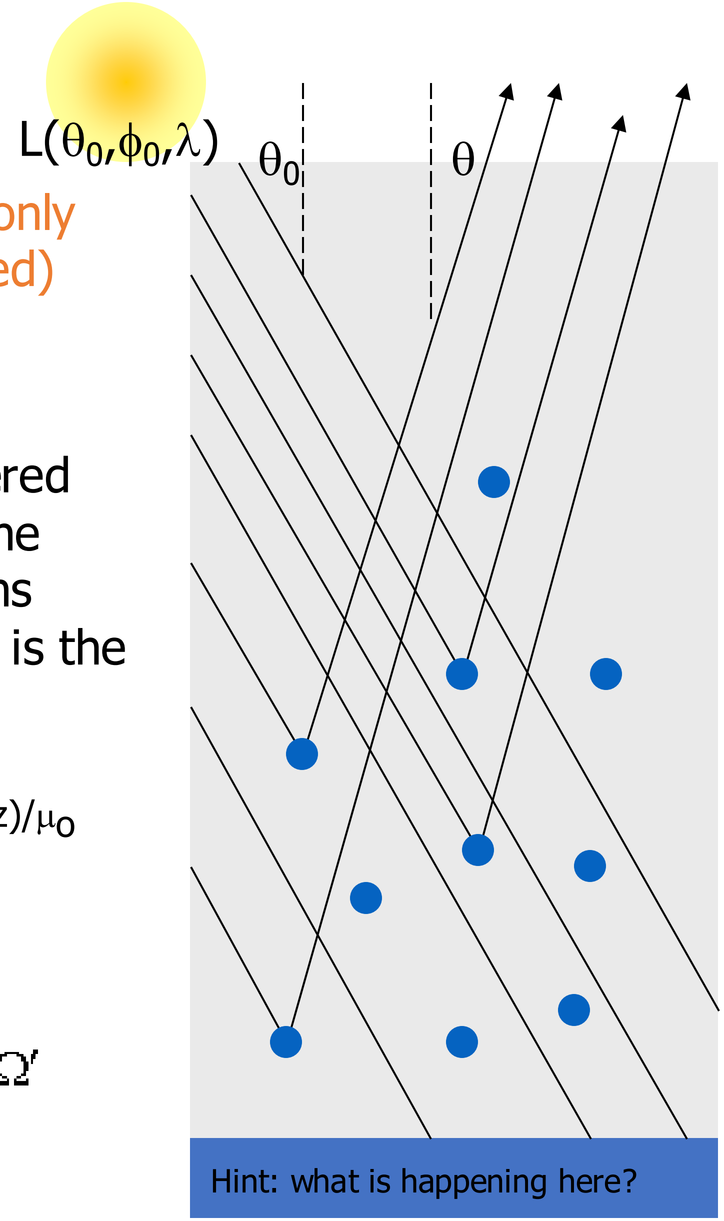
$J = J_{scat}$ only $\qquad \mu_o = \cos\theta_o$

Single scattering implies each photon is scattered only once along the path from the source to the satellite. Therefore, the only source of photons $L(\mathbf{r}',\lambda,\mathbf{X})$ at some place ($\mathbf{X}$) in the atmosphere is the radiance from the source:

$$L(\mathbf{r}',\lambda,\mathbf{X}) = L(\theta_0,\phi_0,\lambda,\mathbf{X}) = L(\theta_0,\phi_0,\lambda)\, e^{-\delta(\lambda,z)/\mu_o}$$

The path radiance is then

$$\int_{4\pi} \gamma_s(\theta,\phi;\theta_0,\phi_0;\lambda,\mathbf{X})L(\theta_0,\phi_0;\lambda)e^{-\delta(\lambda,z)/\mu_0}\,d\Omega'$$
$$= \gamma_s(\psi_s;\lambda,\mathbf{X})L(\theta_0,\phi_0;\lambda)e^{-\delta(\lambda,z)/\mu_0}$$
$$= \frac{\sigma_s(\lambda,z)p(\psi_s)}{4\pi}L(\theta_0,\phi_0;\lambda)e^{-\delta(\lambda,z)/\mu_0}$$



At the top of the atmosphere the result is…

$$L_t(\lambda,\theta,\varphi) = L_0(\lambda,\theta,\varphi)e^{-\delta(\lambda)/\mu} + \int_0^{\delta(\lambda)} \frac{J(\lambda,z;\theta,\varphi)}{\sigma_e(\lambda,z)} e^{-\delta(\lambda,z)/\mu} \frac{d\delta}{\mu}$$

$$L_t(\lambda,\theta,\varphi) = L_0(\lambda,\theta,\varphi)e^{-\delta(\lambda)/\mu} + \int_0^{\delta(\lambda)} \frac{\sigma_s(\lambda,z)p(\psi_s,\lambda,z)}{4\pi\,\sigma_e(\lambda,z)} L(\theta_0,\phi_0;\lambda)e^{-\delta(\lambda,z)/\mu_0} e^{-\delta(\lambda,z)/\mu} \frac{d\delta}{\mu}$$

If we apply this to a single homogeneous layer…

$$L_t(\lambda,\theta,\varphi) = L_0(\lambda,\theta,\varphi)e^{-\delta(\lambda)/\mu} + \frac{\omega_0(\lambda)p(\psi_s,\lambda)}{4\pi} L(\theta_0,\phi_0;\lambda)\underbrace{\int_0^{\delta(\lambda)} e^{-\delta(\lambda,z)(1/\mu+1/\mu_0)} \frac{d\delta}{\mu}}$$

$$L_t(\lambda,\theta,\varphi) = L_0(\lambda,\theta,\varphi)e^{-\delta(\lambda)/\mu} + \frac{\omega_0(\lambda)p(\psi_s,\lambda)L(\theta_0,\phi_0;\lambda)}{4\pi} \frac{[1-e^{-\delta(\lambda,z)(1/\mu+1/\mu_0)}]}{(1/\mu+1/\mu_0)}$$

Radiance that reaches the top of the scattering layer consists of…

Radiance scattered off the surface toward satellite

Probability of transmitting through the atmosphere.

Probability of a scattering interaction (rather than an absorption)

Radiance entering the top of the layer

Probability of the scattered radiance being directed toward the satellite (θ,ϕ)

Probability of an interaction with a scatterer (1 - the probability of no interaction)

MR3522: Remote Sensing of the Atmosphere and Ocean

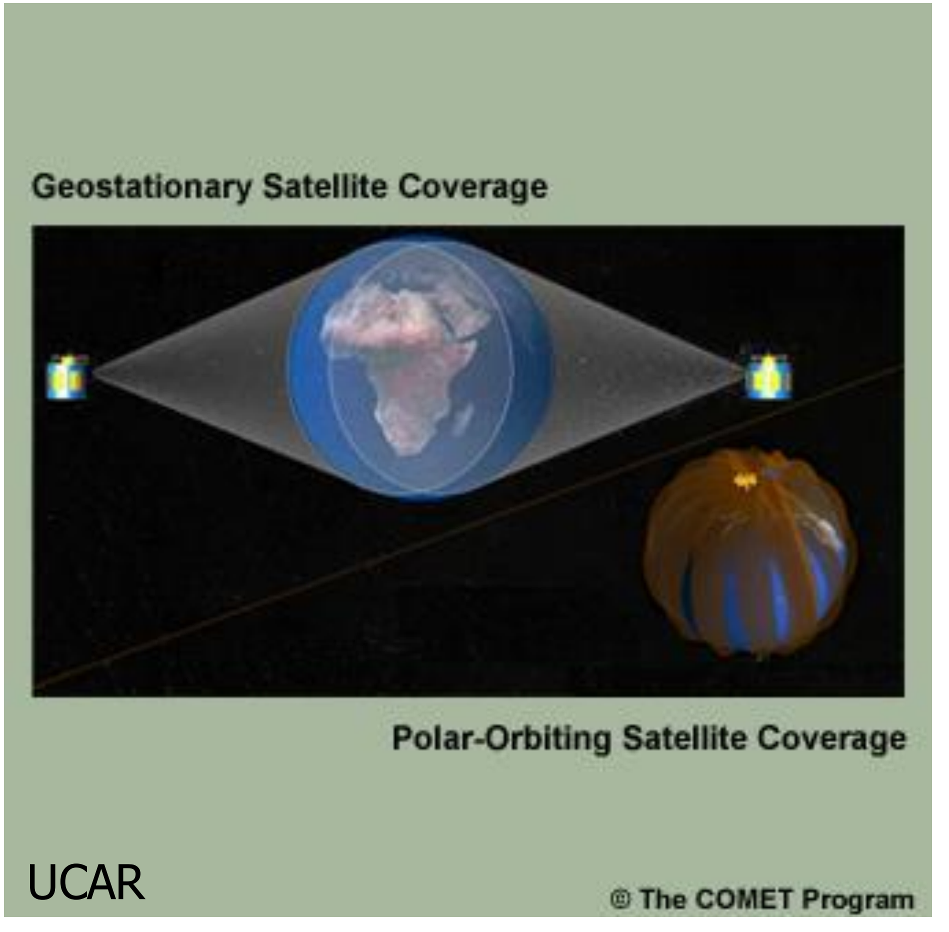
Medium-to-high satellite orbits

Main Topics

- Orbital characteristics
- Geosynchronous/geostationary orbits
- Semi-synchronous orbit
- Molniya orbit

Why are orbits important?

1. Orbit controls the viewable area from the satellite.
2. Orbit determines the **orientation/projection** of a satellite **image**



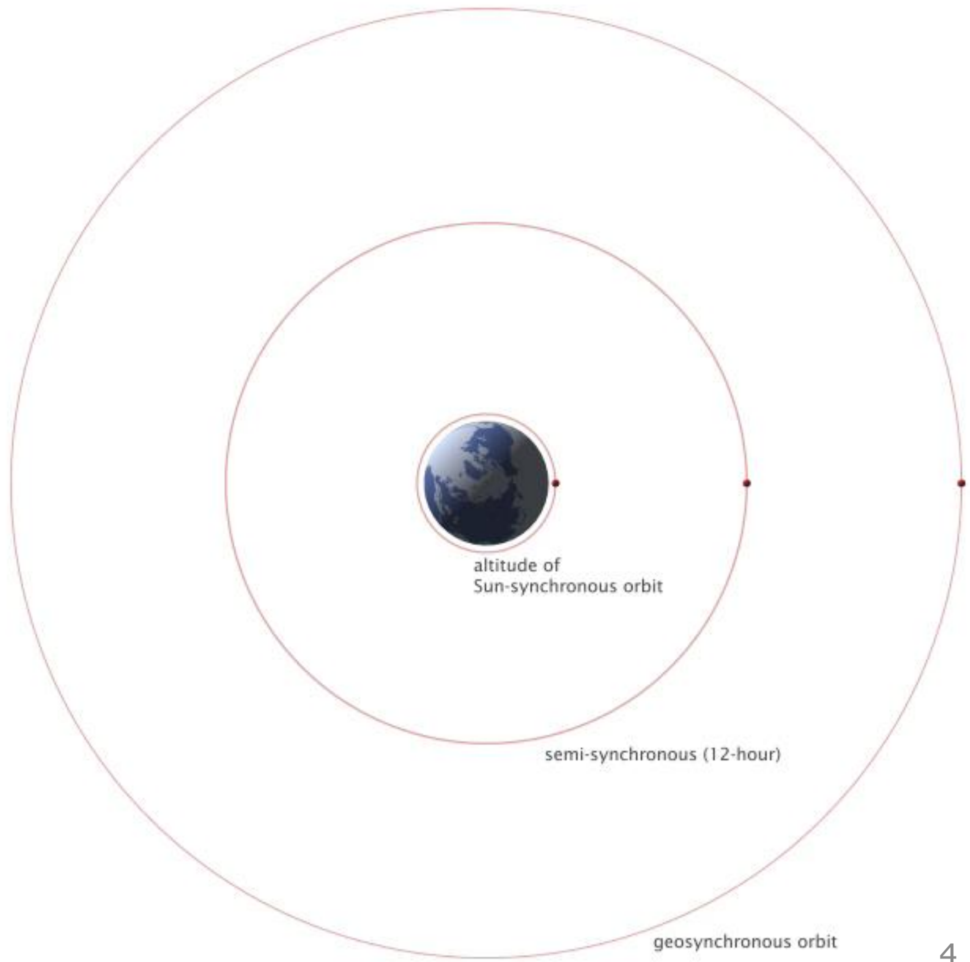
An orbit is defined by its **height** from the center of Earth**.**

Orbiting satellite motions are controlled by Earth's gravity.

Satellite in low orbit must travel faster to balance increased gravitational force.

	LEO	GEO
Height [km]	<850 km	~35,786
Velocity [km/h]	~28164	~11265
Orbital Period (T) [min]	~90	1436 (23h, 56m, 4s)

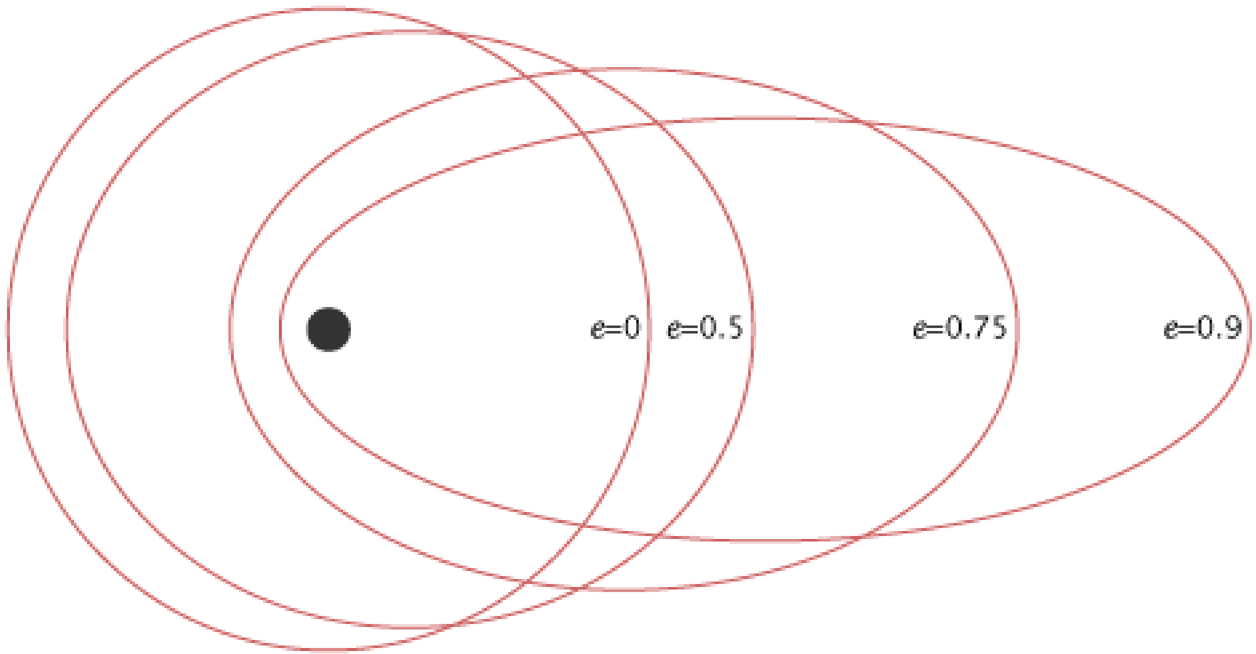
Height from the surface of Earth



An orbit is defined by its **eccentricity.**

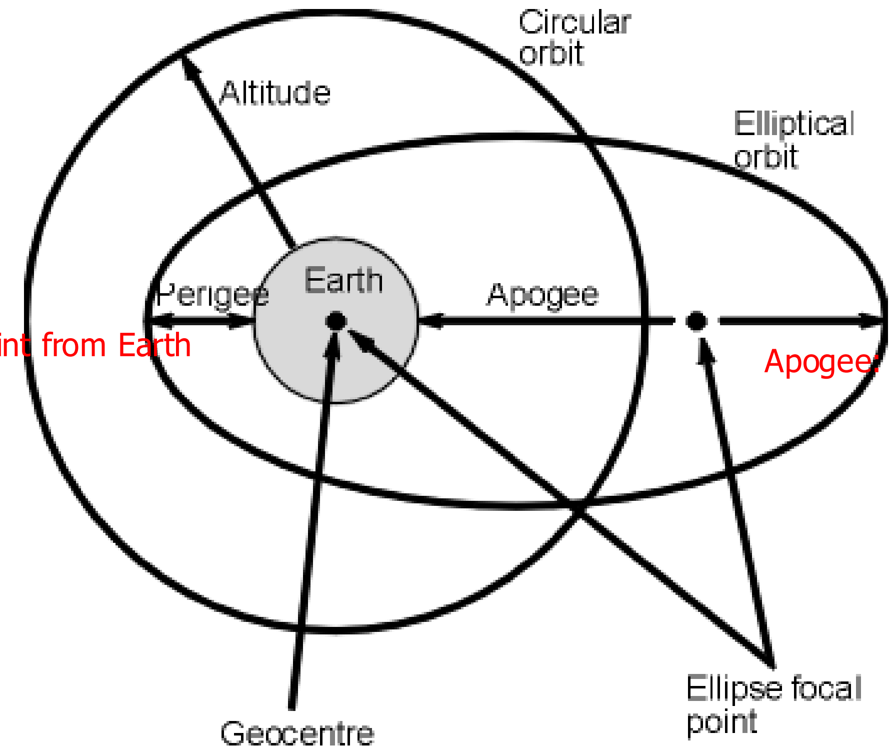
Eccentricity refers to the shape of the orbit.

- Low eccentricity orbit -> nearly circular orbit
- Eccentric orbit -> elliptical orbit
    - the satellite’s distance from Earth changing depending on where it is in its orbit.



Circular orbit:
For a circular orbit, the distance from the Earth remains the same at all times.

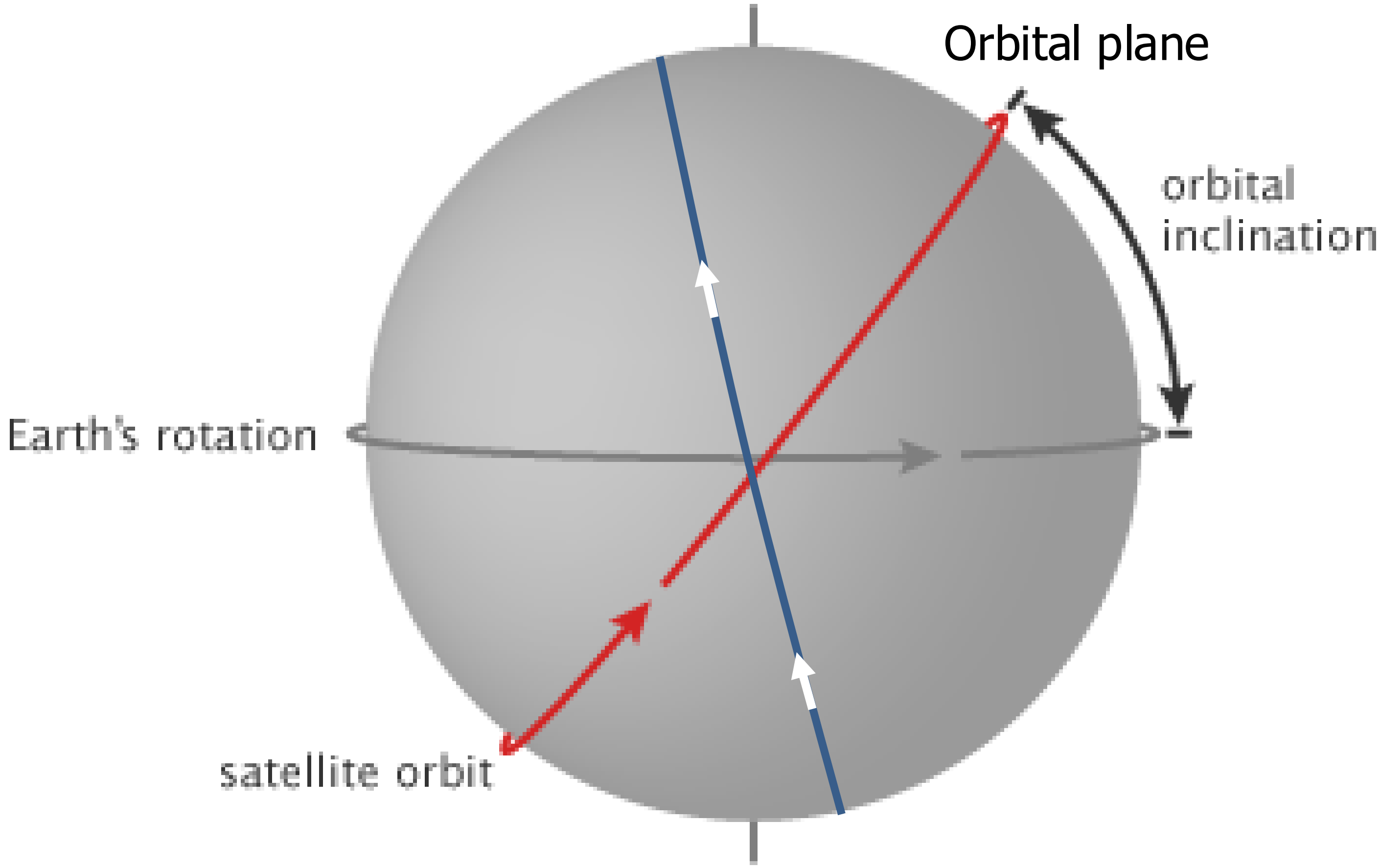
Ellipitical orbit:
An elliptical orbit changes the distance to the Earth



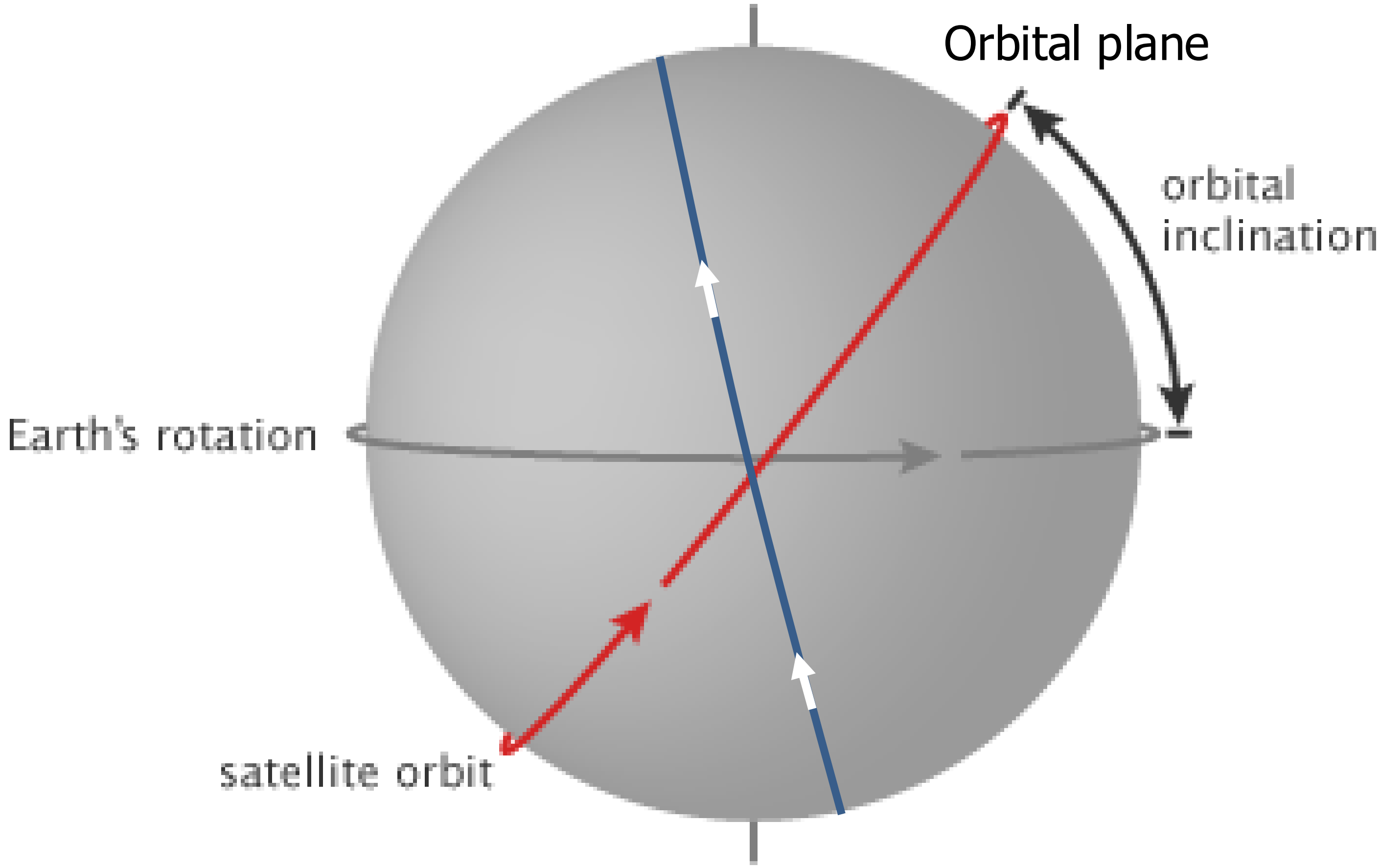
Perigee: Closest point from Earth

Apogee: Farthest point from Earth

An orbit is defined by its **inclination.**



An orbit is defined by its **inclination.**



> 90° inclination (retrograde orbit)

Most environmental satellite orbits are nearly circular.

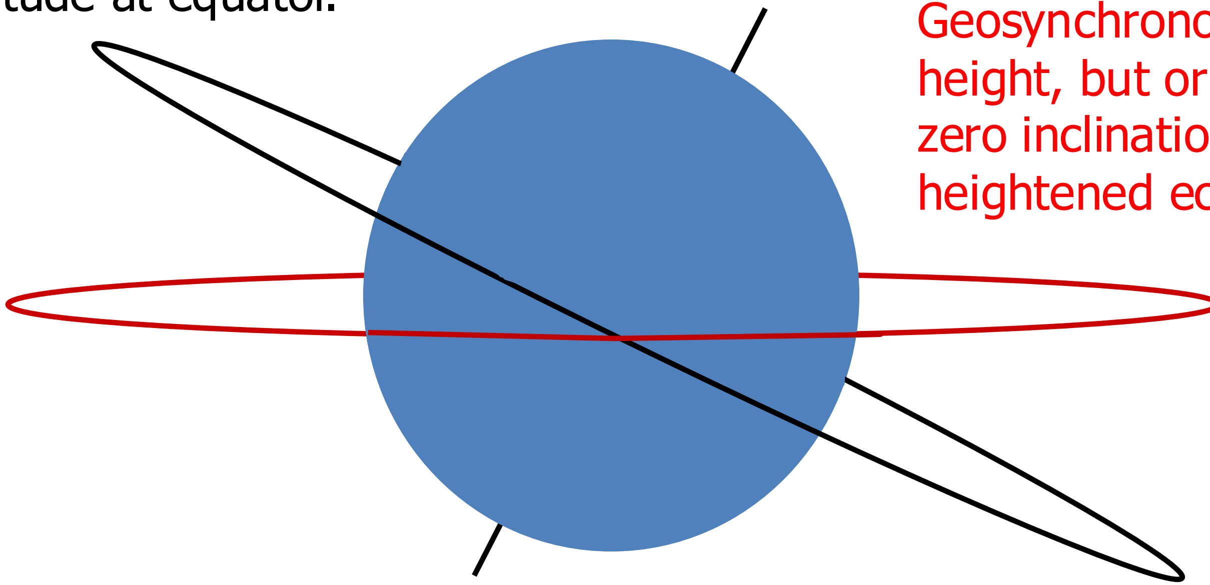
Perturbations are caused by:

1. aspherical gravitational potential (the Earth is not quite a sphere)
   most important - leads to precession of an orbit
2. other gravitational bodies (sun, moon, etc..)
3. atmospheric drag - important below 850 km
4. atmospheric lift
5. solar radiation pressure
6. galactic particle bombardment (solar wind and cosmic ray flux)
7. electromagnetic field asymmetry

Geosynchronous/geostationary orbits

Geostationary: Fixed over
some longitude at equator.

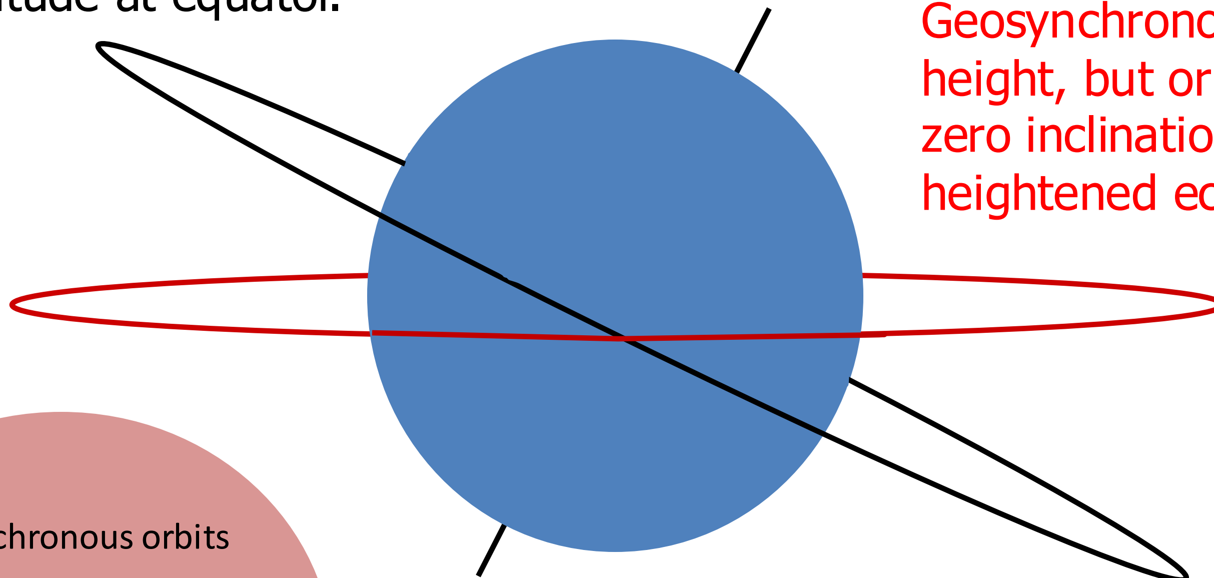
Geosynchronous*: Has same
height, but orbit has non-
zero inclination or
heightened eccentricity.

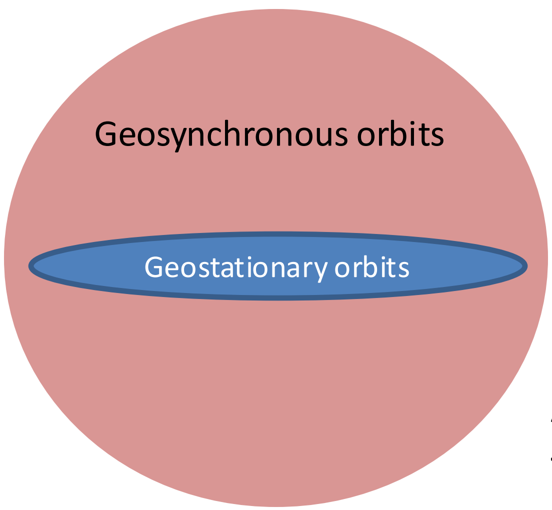


Geosynchronous orbits have can inclination and eccentricity that can largely offset each other’s longitudinal or latitudinal drift (frozen orbits).

Geostationary: Fixed over some longitude at equator.

Geosynchronous*: Has same height, but orbit has non-zero inclination or heightened eccentricity.





A geostationary orbit is a special type of geosynchronous orbit.

Geosynchronous orbits have can inclination and eccentricity that can largely offset each other's longitudinal or latitudinal drift (frozen orbits).

Let’s look at how Newton’s laws of motion describe the motions of celestial bodies in general and the orbits of satellites in particular.

$$F_c = m_s a = m_s \frac{v^2}{r}$$

Centripetal force

$$F_g = \frac{G m_e m_s}{r^2}$$

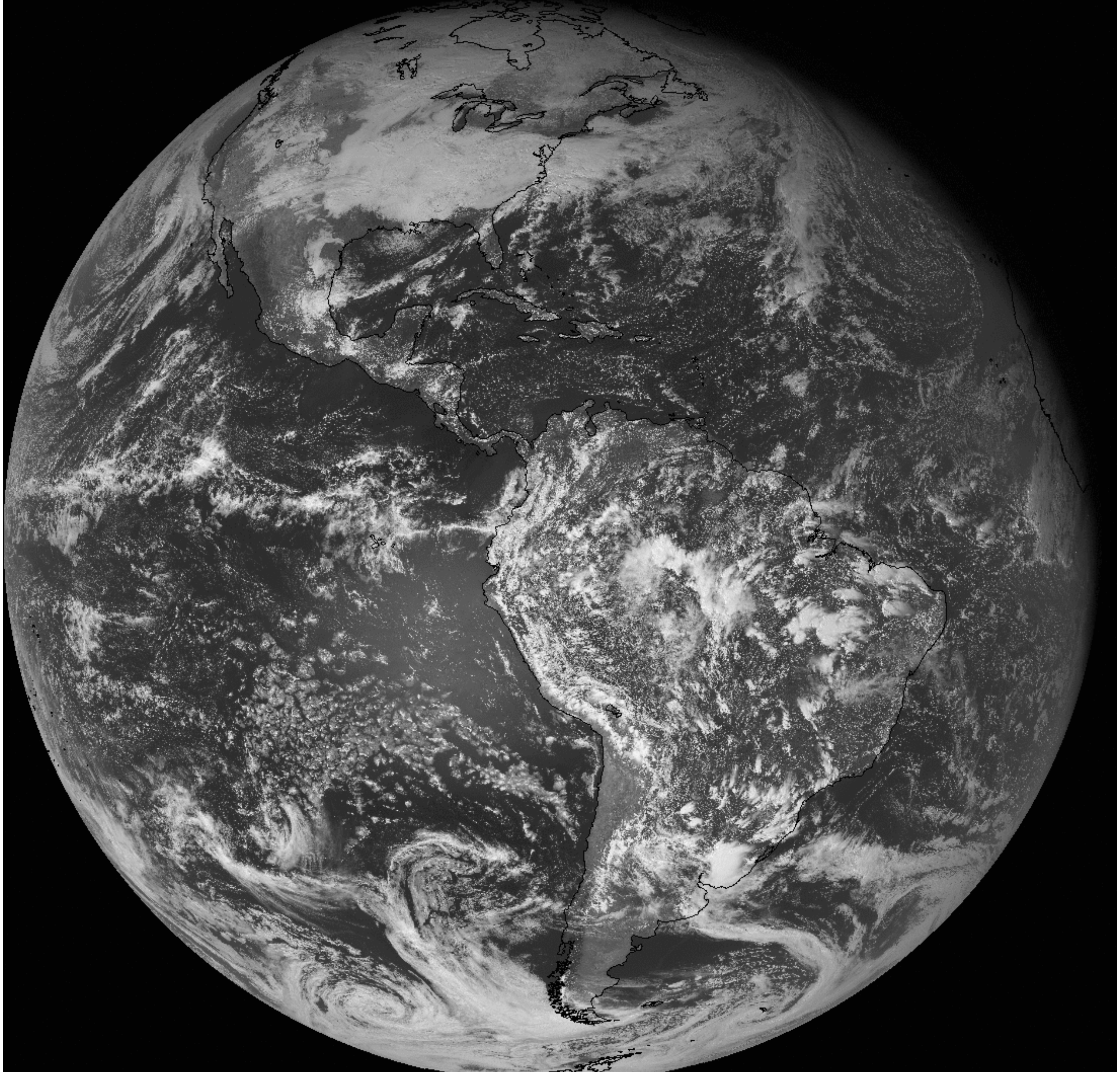
Gravitational force

$$T = \frac{2pr}{v}$$

$$2pr = circular\_orbit$$

$$T^2 = \frac{4p^2 r^3}{G m_e}$$

Or rearrange to solve for radius of orbit.



Benefits of geostationary orbit:

(1) large spatial coverage (five geostationary satellites are enough to cover all of the non-polar regions of the Earth).

(2) permanent visibility of the satellite allowing continuous telecommunications and high rate of repetition for observations (near continuous time sampling - 30 min and 15 min for Meteosat, a few minutes for GOES).

Disadvantages of geostationary orbit:

(1) polar regions are not observed.

(2) Not adequate for high spatial resolution of the ground (although this is improving; up to 500 meters x 500 meters at nadir for GOES red channel!)

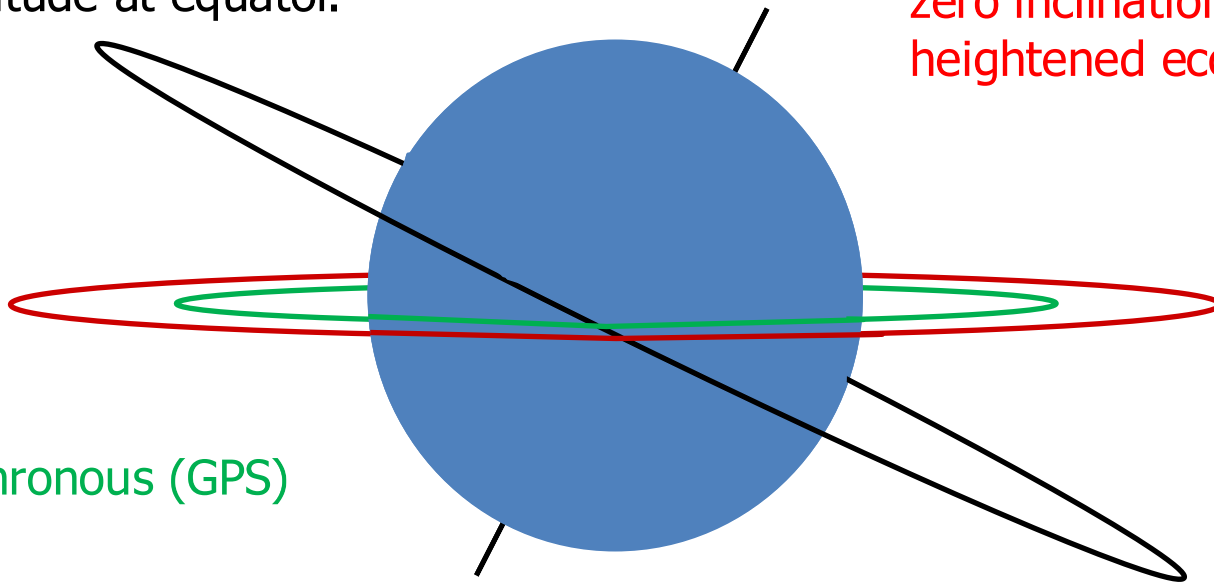
(3) active measurements are not reasonably feasible at such a distance from the Earth.

(4) some perturbations of the solar electricity power supply to the satellite occur during eclipses of the sun.

Medium Earth Orbit
Semi-synchronous orbit and Molniya orbit

Geostationary: Fixed over some longitude at equator.

Geosynchronous*: Has same height, but orbit has non-zero inclination or heightened eccentricity.



Semi-synchronous (GPS)

Medium Earth Orbit

Closer to the Earth; therefore, satellites move more quickly than geostationary orbiters.

Semi-synchronous orbit:

- near-circular orbit (low eccentricity)
- 26,560 kilometers from the center of the Earth (about 20,200 kilometers above the surface).
- 12 hours to complete an orbit
- GPS operates at inclination of 55°

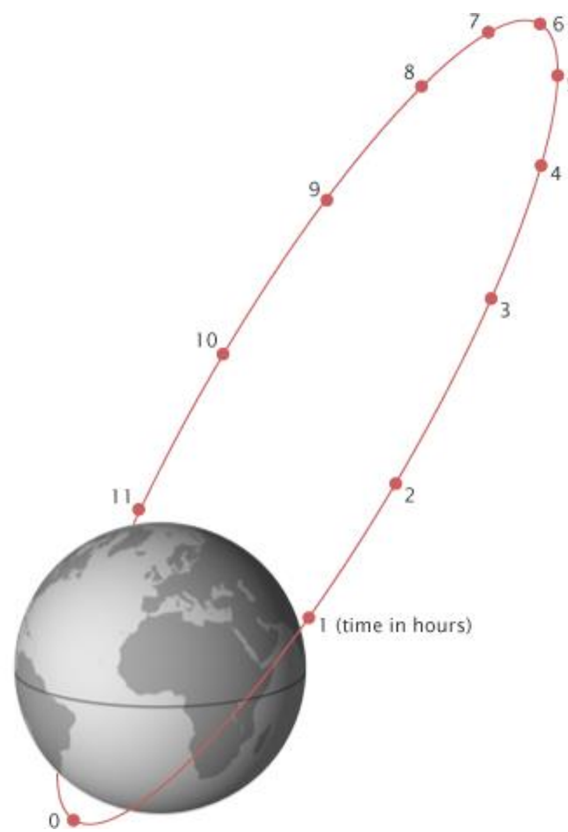
This orbit is consistent and highly predictable.

Semi-synchronous orbit is used by the Global Positioning System (GPS) satellites so is important for GPS radio occultation estimates of temperature and humidity.

Molniya Orbit

A satellite in a highly eccentric orbit spends most of its time in the neighborhood of apogee, which for a Molniya orbit in this configuration is over the northern hemisphere.

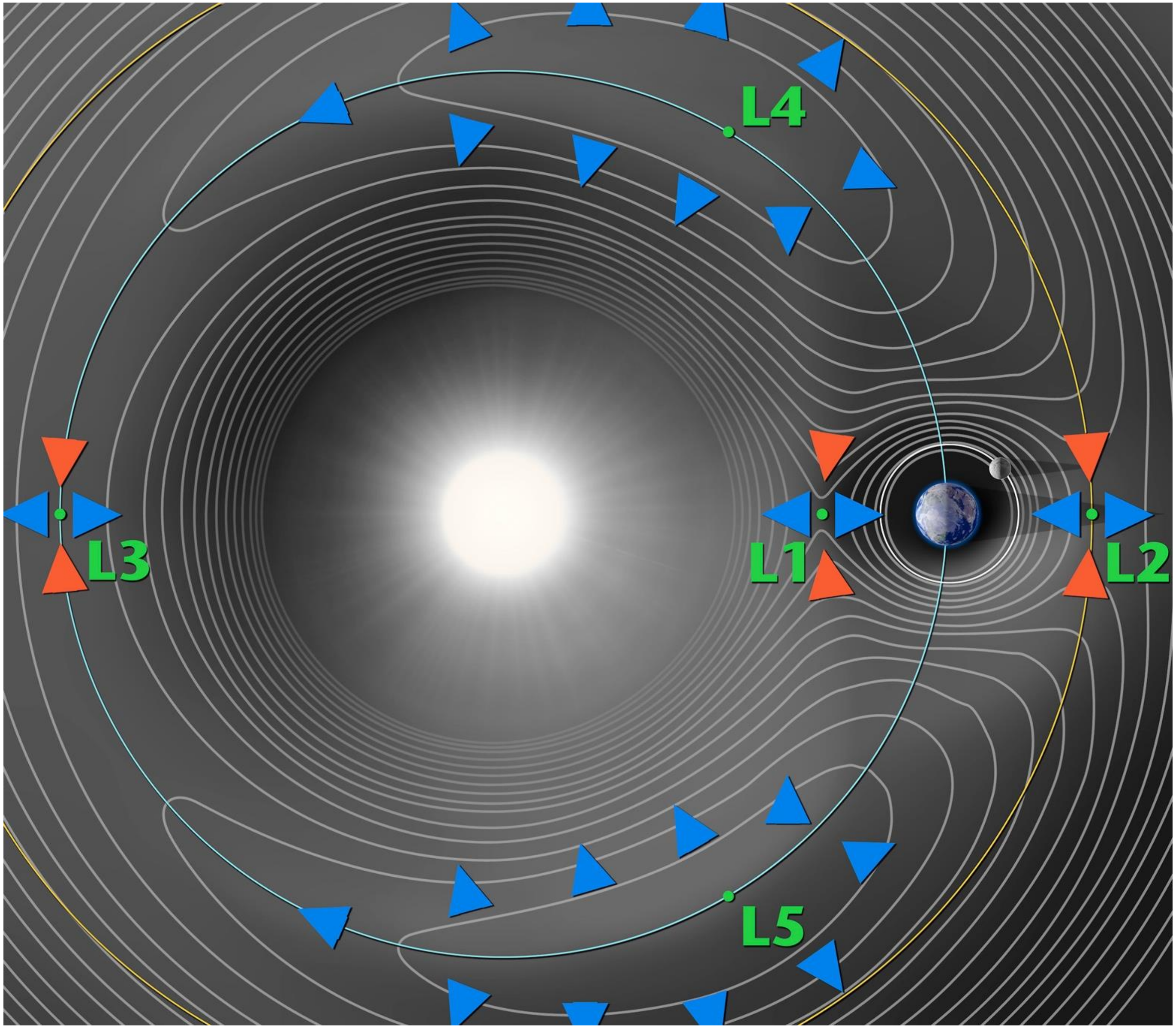
Inclination of ~63.4°
Period of about ½ day
Apogee is around 40,000 km



Wikipedia

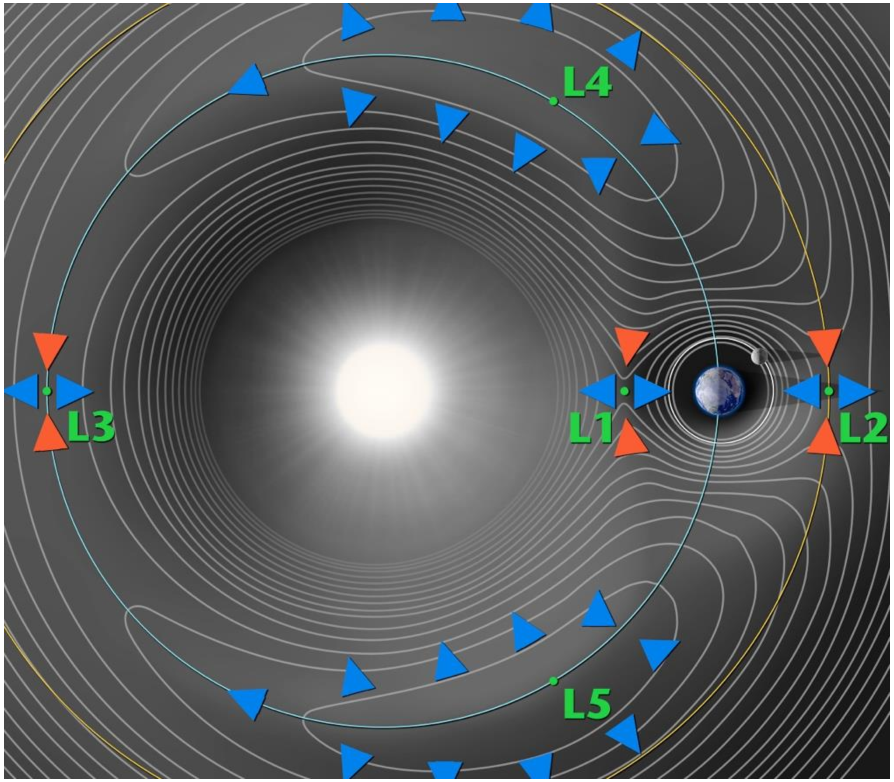
Ground track (sub-satellite point)

Lagrange Points



Source: NASA

Lagrange Points



Source: NASA

Mechanically stable points for the Earth-Sun orbit. At these points, gravity of the two bodies is balanced by centripetal force.

L1: Located between Sun and Earth. (DSCOVR)

L2: Located behind Earth (James Webb telescope)

L3, L4, L5: Located in an equilateral triangle at high points in the gravitational potential function. L4 and L5 have natural objects in stable orbits around these points.

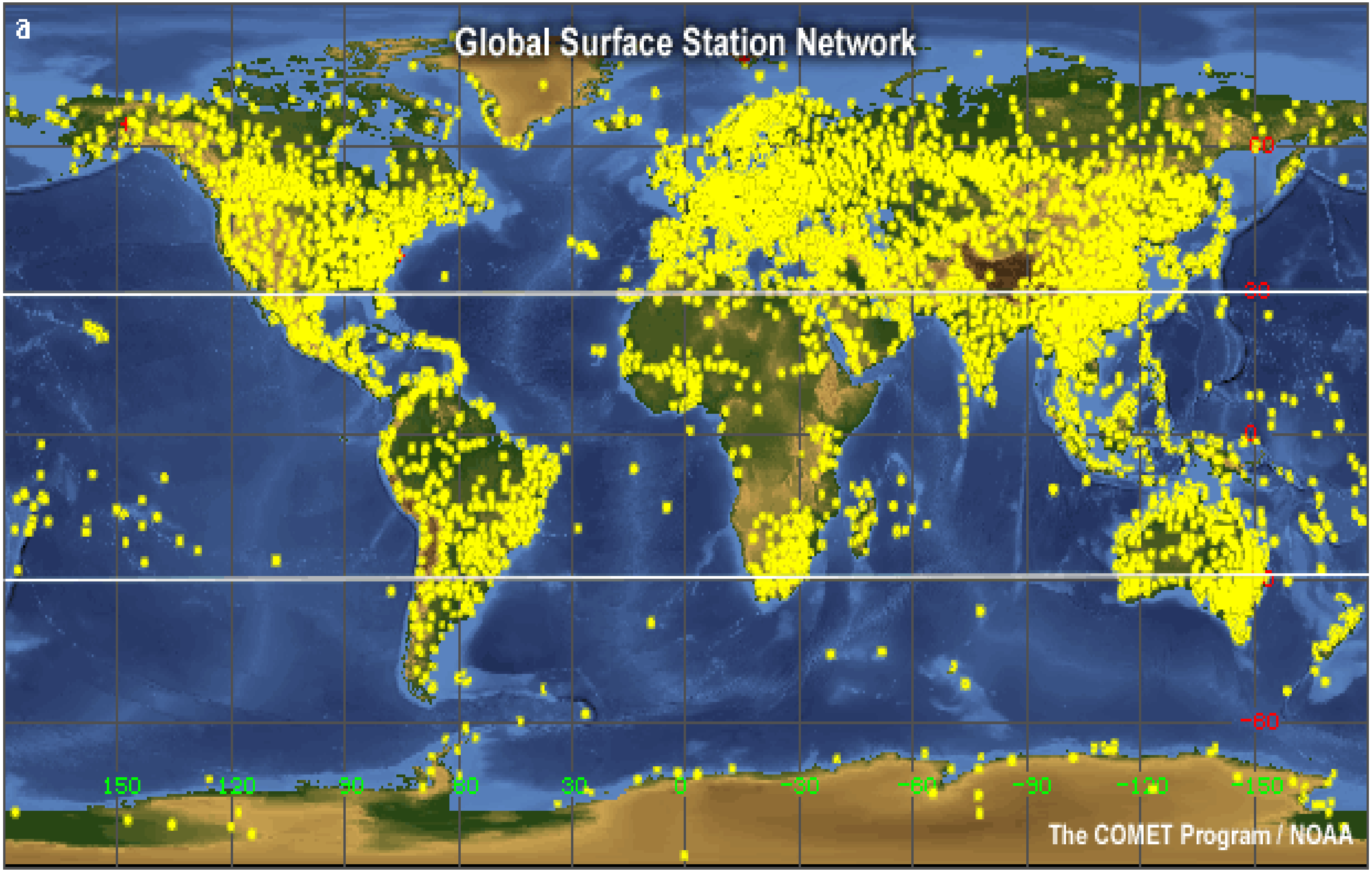
L1, L2, and L3 are unstable orbital locations!

MR3522: Remote Sensing of the Atmosphere and Ocean

Low-Earth orbits (LEO)

Main Topics

- Sun-synchronous orbits
- Ascending and descending orbits
- Effect of inclination on low-earth orbits



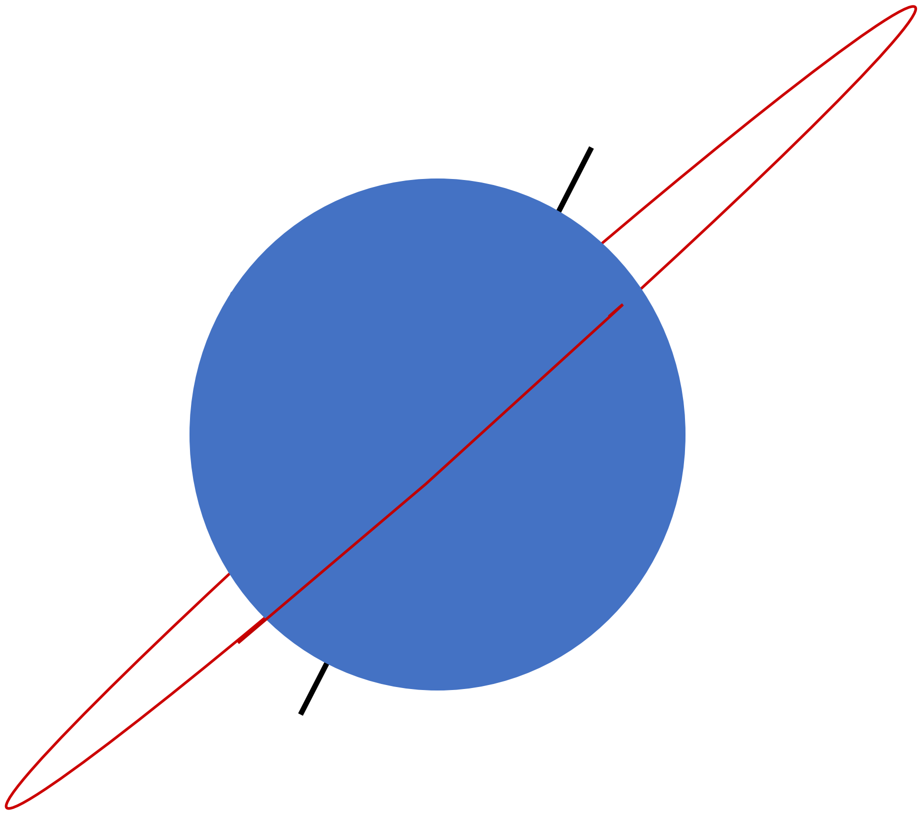
Most of Earth lacks surface and rawinsonde observations!

Low-Earth orbit satellites

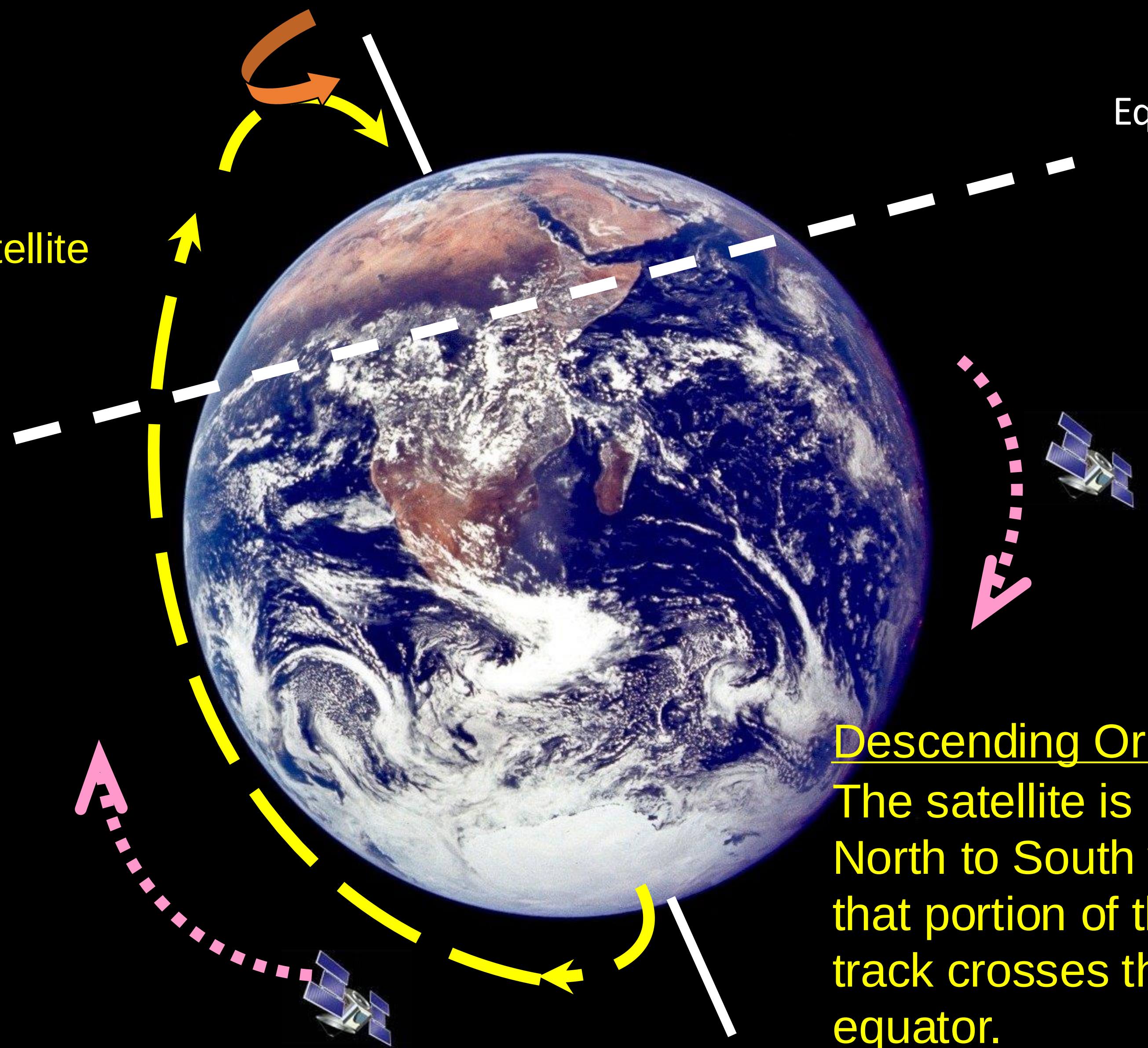
1. Circular orbit with high inclination collecting data in a swath beneath them as the Earth rotates on its axis.

2. Able to collect data from large portion of Earth, including high latitudes.

3. Low orbit permits active sensing and high spatial resolution.



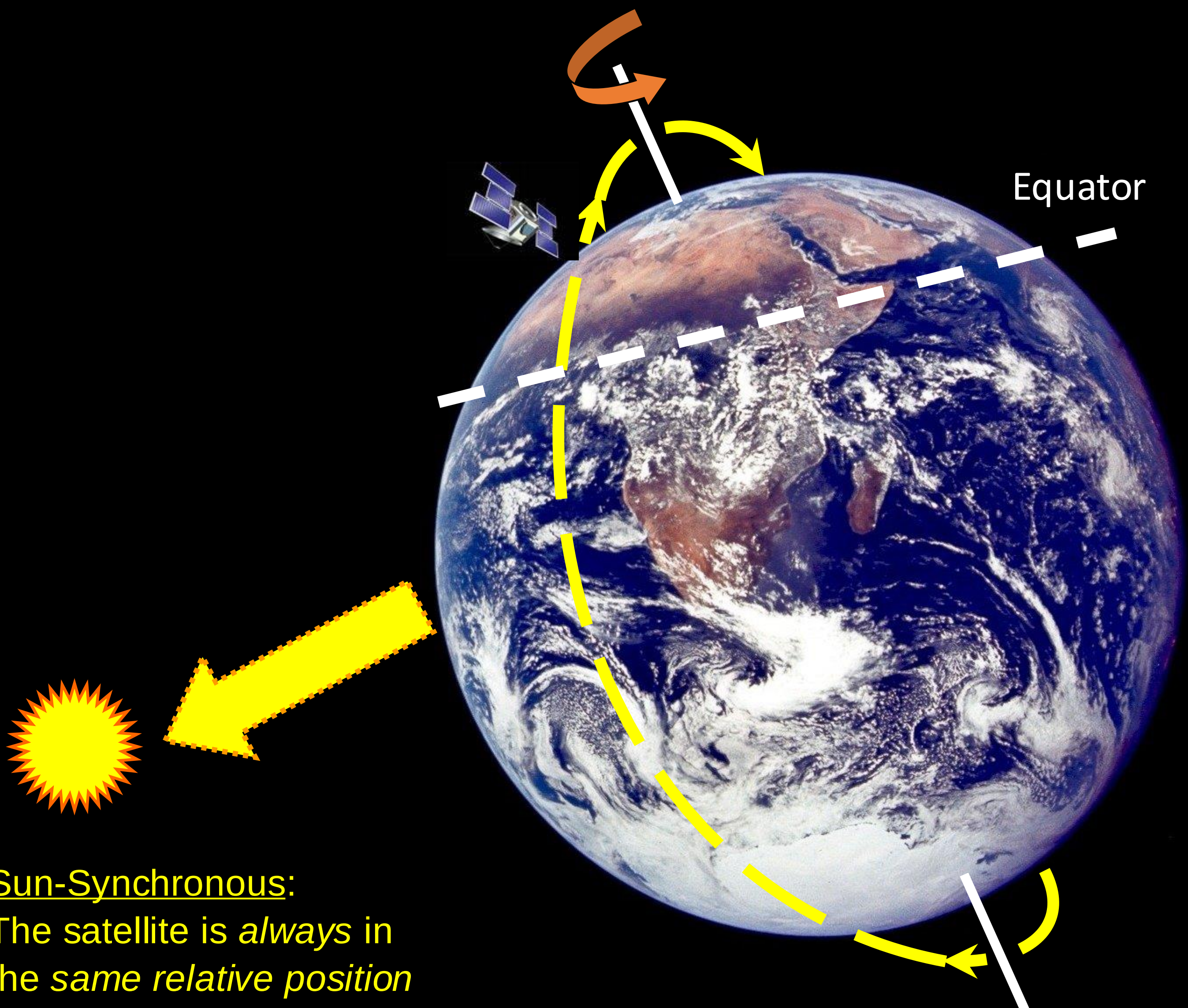
Low-Earth Orbits (LEO)



<u>Ascending Orbit</u>:
The satellite is moving South to North when that portion of the orbit track crosses the equator.

<u>Descending Orbit</u>:
The satellite is moving North to South when that portion of the orbit track crosses the equator.

Low-Earth Orbits (LEO)

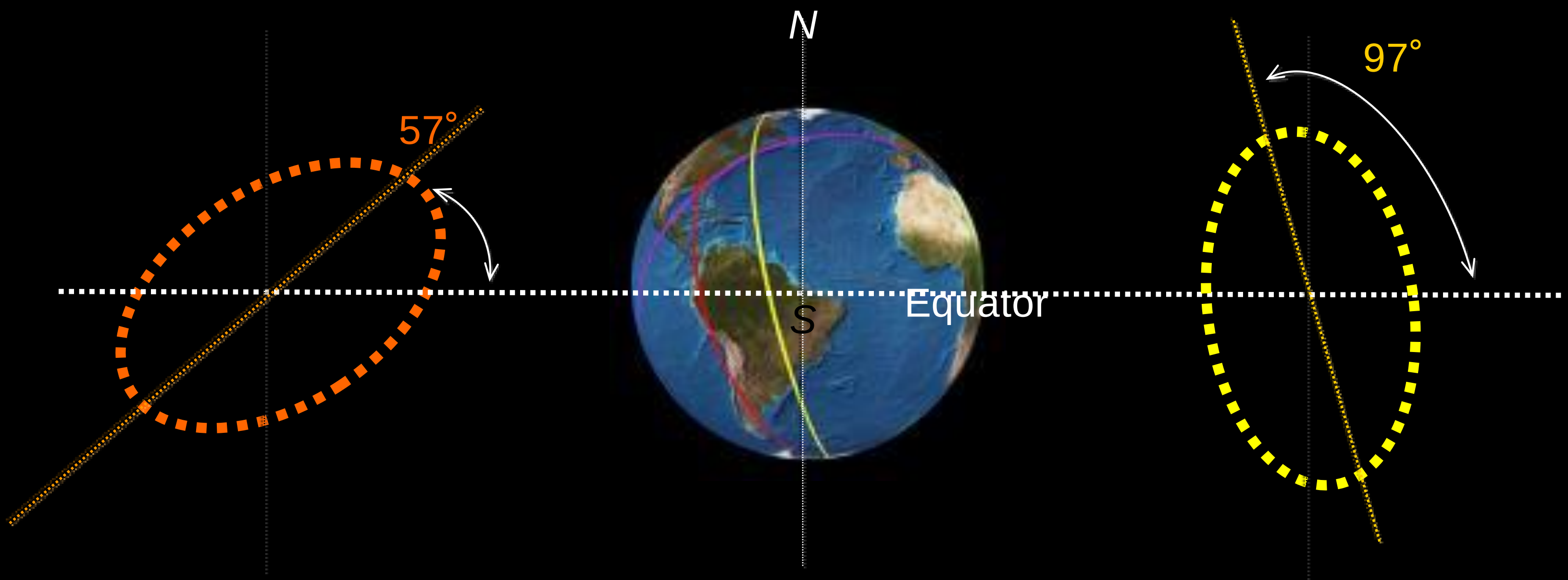


<u>Equator-Crossing Time</u>:
The local apparent solar time when the satellite crosses the equator.

Example: Terra has an equatorial crossing time of 10:30 am, and is called an "AM" or morning satellite. (i.e. Terra)

<u>Sun-Synchronous</u>:
The satellite is *always* in the *same relative position* between the Earth and Sun

Orbital Inclination



<u>Inclination</u>:
The position of the orbital plane relative to the equator.
For near-polar orbits, typically about 98º.

Low Inclination Orbit (often near 57º-- Space Shuttle, TRMM, GPM at 65º)

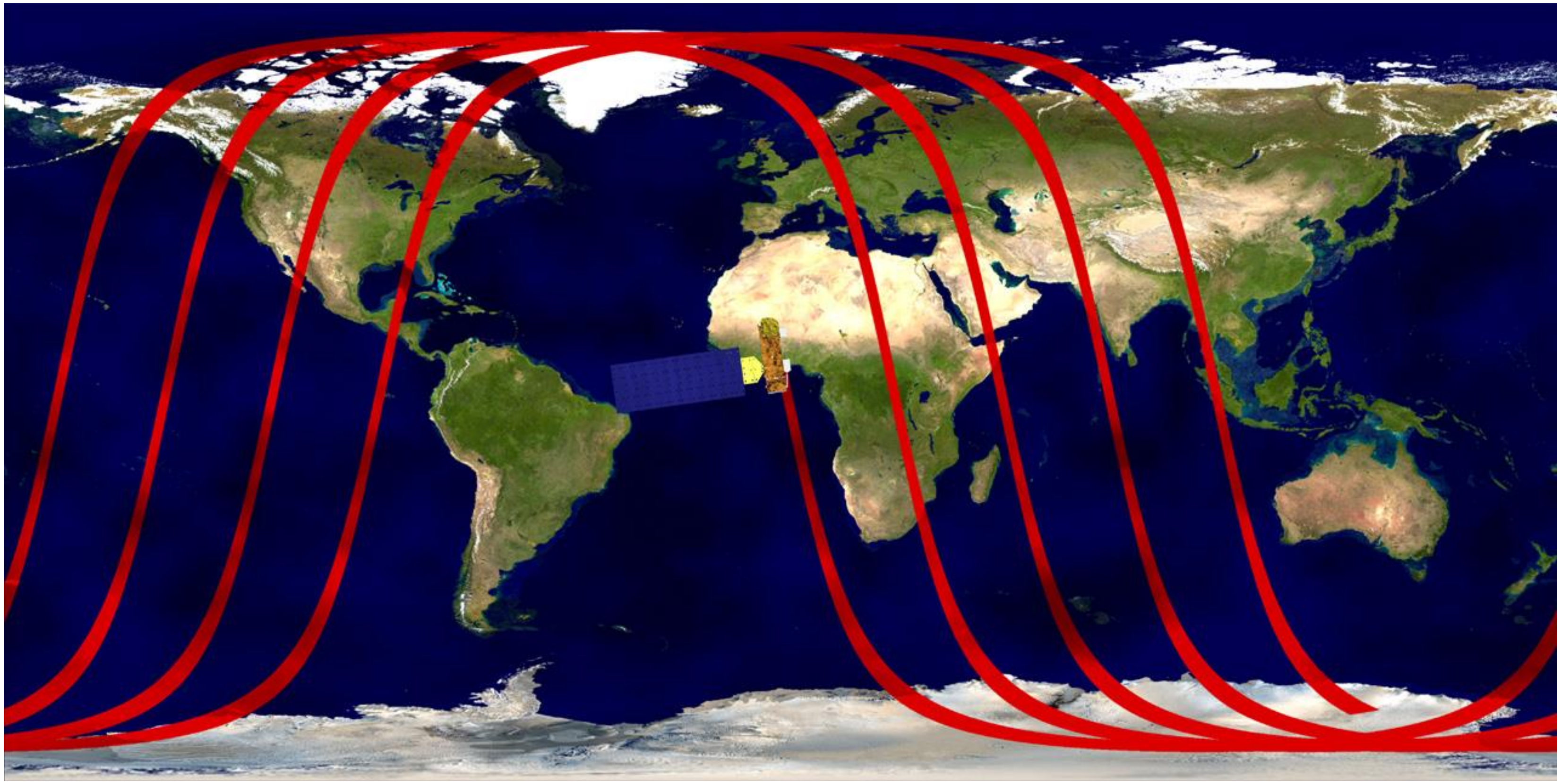
no polar coverage

High Inclination or Polar Orbit (near 90º)

virtually complete global coverage

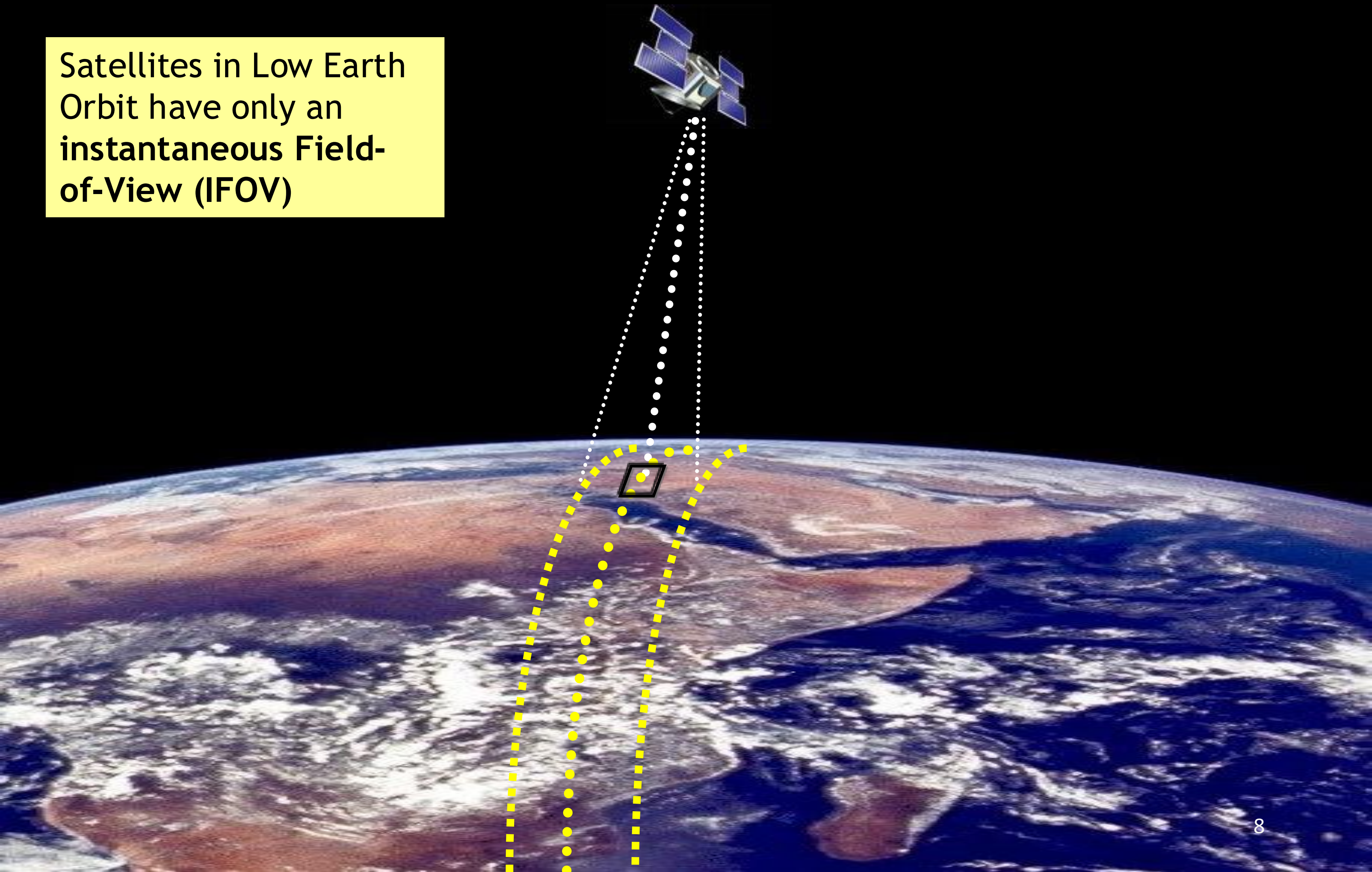
Aqua’s Orbit

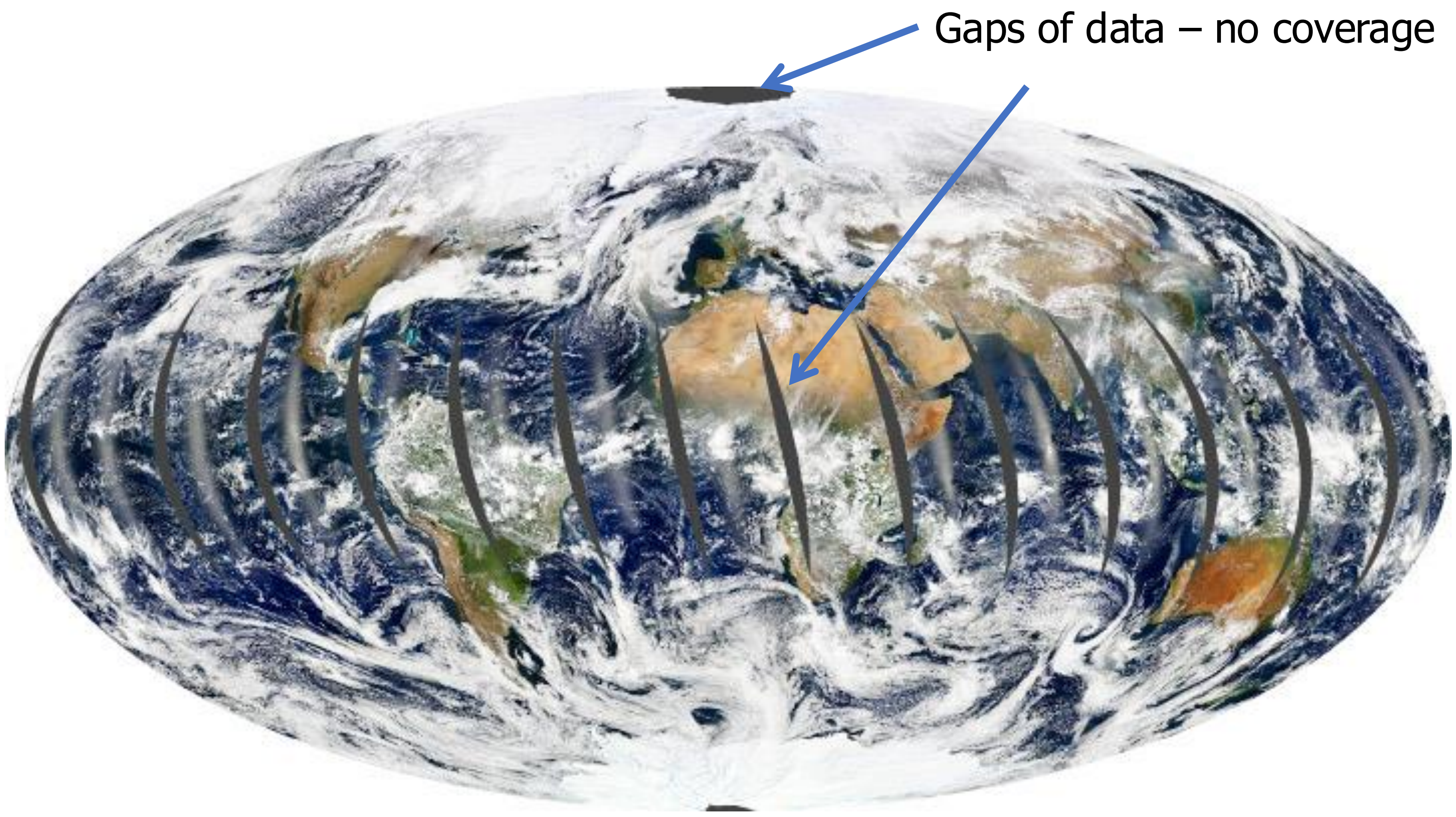
- Near-polar, sun-synchronous, orbiting the Earth every 98.8 minutes, crossing the equator going north (daytime ascending) at 1:30 p.m. and going south (night time descending) at 1:30 a.m.
- The orbit track changes every day but will repeat on a 16 day cycle. **This is true for Aqua, Terra, and previously, TRMM.**



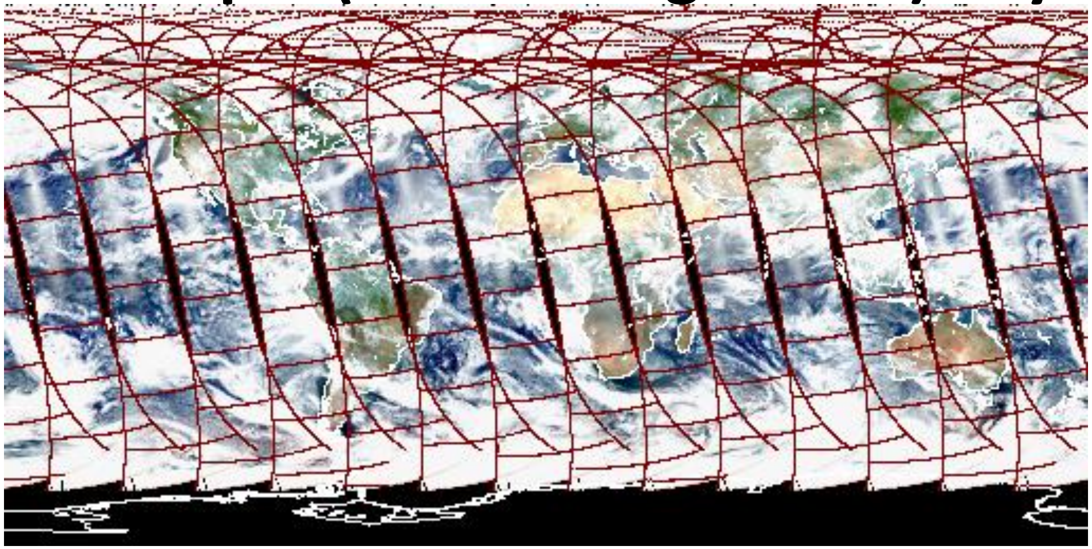
LEO Field-of-View (FOV)

Satellites in Low Earth Orbit have only an **instantaneous Field-of-View (IFOV)**



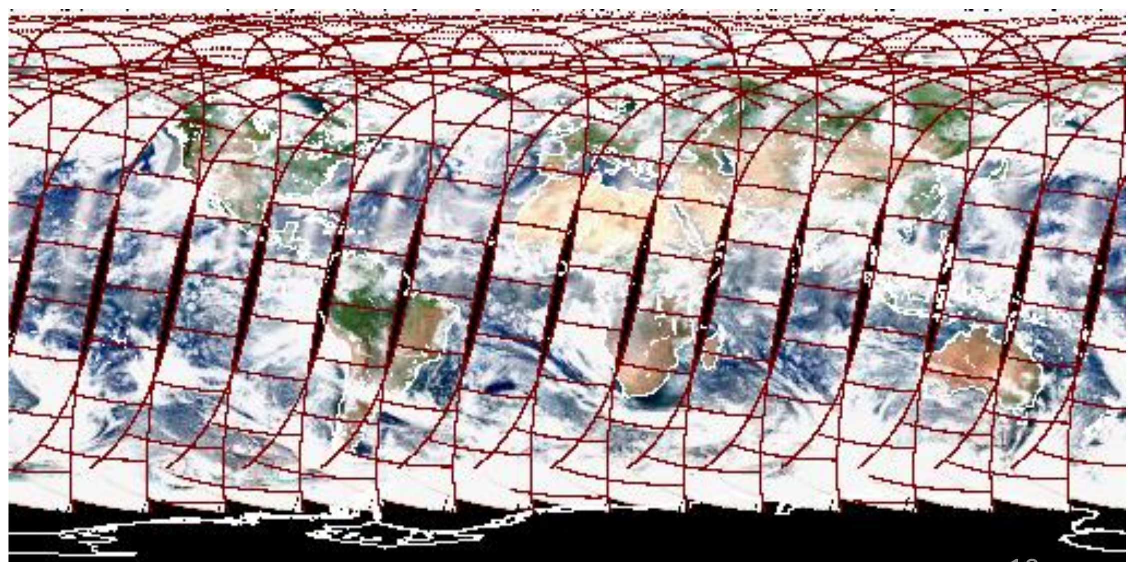

Gaps of data – no coverage

Aqua (“ascending” orbit) day time



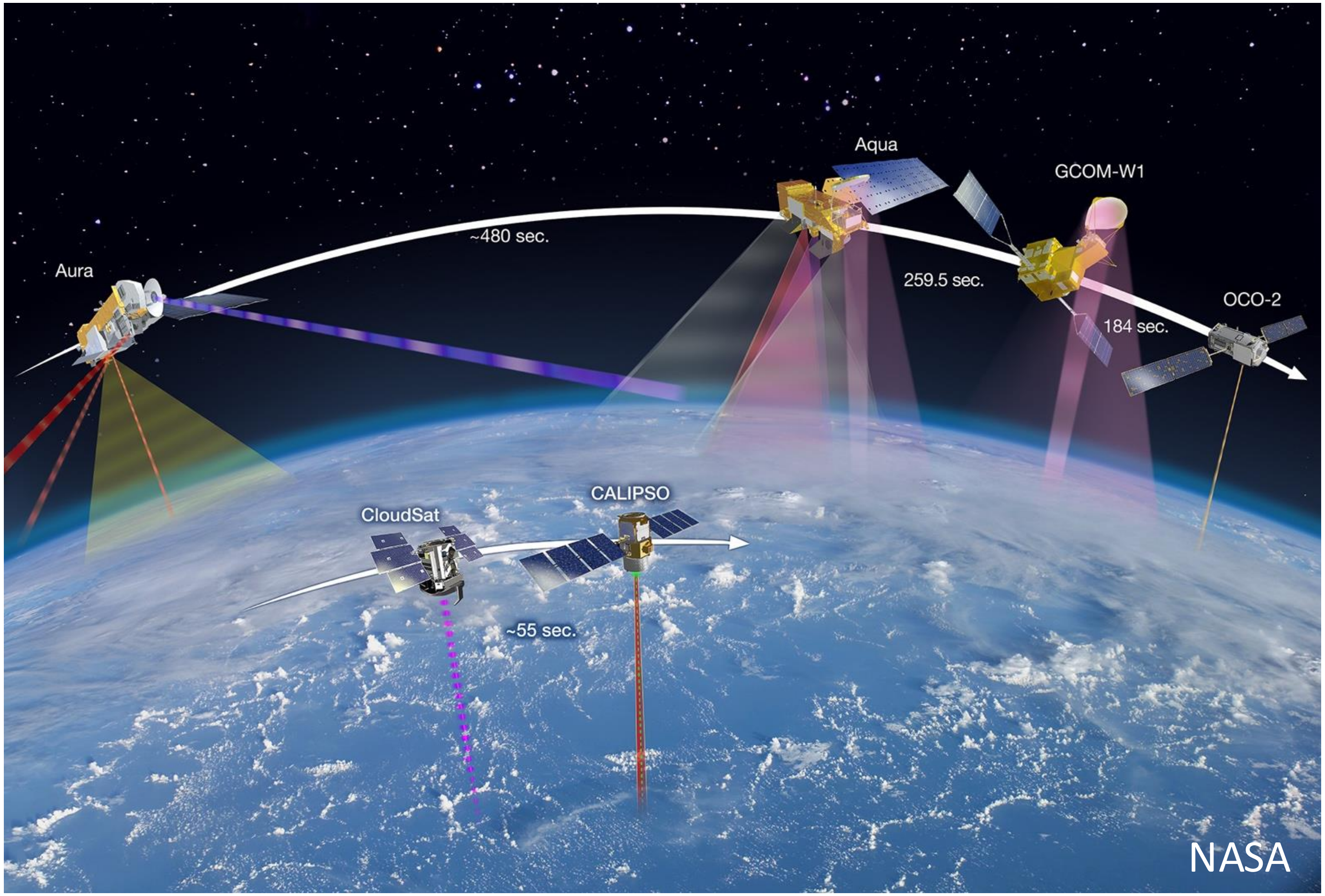
LEO Sun-synchronous Orbiting

Terra (“descending”) Day time



- By flying satellites in formation through the A-Train, NASA is capable of making unique, global, near-simultaneous measurements of aerosols, clouds, temperature and relative humidity profiles, and radiative fluxes.

- CloudSat and CALIPSO exited the A-Train in 2018, and entered a lower orbit, now called the "C-Train". Eventually, the satellites will be decommissioned and destroyed upon re-entry.



Satellite	Instrument		Measurement
Aura 	HIRDLS*	High-Resolution Dynamics Limb Sounder ***Inoperative since 2008**	Temperature and composition of the upper troposphere, stratosphere, and mesosphere; aerosol extinction and cloud height
	MLS	Microwave Limb Sounder	Temperature and composition of the upper troposphere and stratosphere; upper tropospheric cloud ice
	OMI	Ozone Monitoring Instrument	Total column ozone, nitrogen dioxide, sulfur dioxide, formaldehyde, bromine monoxide, aerosol absorption, and cloud centroid pressure
	TES*	Tropospheric Emission Spectrometer ***Inoperative since 2018**	Temperature, ozone, carbon monoxide, and water vapor profiles from the surface to lower stratosphere
PARASOL* 	POLDER	POLarization and Directionality of Earth's Reflectances ***Inoperative since 2013**	Polarized light measurements of clouds and aerosols
CloudSat 	**CPR**	Cloud Profiling Radar	Vertical profiles of water amount measured by back-scattered radar signals from clouds
CALIPSO 	**CALIOP**	Cloud-Aerosol Lidar with Orthogonal Polarization	High-resolution vertical profiles of aerosols and clouds
	IIR	Imaging Infrared Radiometer	Nadir-viewing, non-scanning imager
	WFC	Wide Field Camera	Fixed, nadir-viewing imager with a single spectral channel covering a portion of the visible (620–670 nm) region of the spectrum to match Band 1 of the MODIS instrument on Aqua (see below)
Aqua 	**AIRS**	Atmospheric Infrared Sounder	Highly accurate temperature profiles within the atmosphere
	AMSR-E*	Advanced Microwave Scanning Radiometer for Earth Observing System ***Inoperative since 2015**	Precipitation rate, cloud water, water vapor, sea-surface winds, sea-surface temperatures, ice, snow, and soil moisture
	AMSU-A	Advanced Microwave Sounding Unit-A	Temperature profiles in the upper atmosphere, especially in the stratosphere
	CERES	Cloud's and Earth's Radiant Energy System	Solar-reflected and Earth-emitted radiation; cloud propertiest (altitude, thickness, and size of the cloud particles)
	HSB*	Humidity Sounder for Brazil ***Inoperative since 2003**	Humidity profiles throughout the atmosphere
	MODIS	MODerate-resolution Imaging Spectroradiometer	Vegetation, land surface cover, ocean chlorophyll fluorescence, cloud and aerosol properties, fire occurrence, land snow cover, and sea ice cover
GCOM-W1 	**AMSR2**	Advanced Microwave Scanning Radiometer, second generation	Enhanced understanding of water in Earth's climate system and the global water cycle, and of additional components of Earth's climate system and their interactions
OCO-2 	Three high-resolution grating spectrometers		Full-column measurements of CO_2

Summary of Orbits Used in Earth Observation

Type of orbit	Description of Orbit and/or Data	Examples
Geostationary (GEO)	Sub-satellite point stationed at same position; continuous coverage of large area	GOES, Himawari, METEOSAT, INSAT, Feng-Yun, Electro
Semi-Synchronous orbit (1 rotation every 12 hours)	GPS Radio Occultation	GPS satellites
Molniya orbit	High eccentricity; Used for communications or observation at mid to high latitudes	Arctica (planned)
Sun-synchronous orbit	LEO; Each crossing of the equator is at the same local solar time; inclination is about 98° and depends on height (600–800 km)	A-Train constellation, Landsat,WorldView, MetOp-A,B, QuikSCAT, Suomi-NPP, DMSP, Terra, SPOT, NOAA-18 and 19, and many, many more
Non sun-synchronous orbits (drifting orbits)	Global coverage in longitude, but latitudinal coverage determined by inclination.	GPM, TRMM, Jason, Cryosat, GRACE, Megha-Tropiques, many nanosatellites clusters,

List of all Earth observation satellites:
https://www.wmo-sat.info/oscar/satellites