

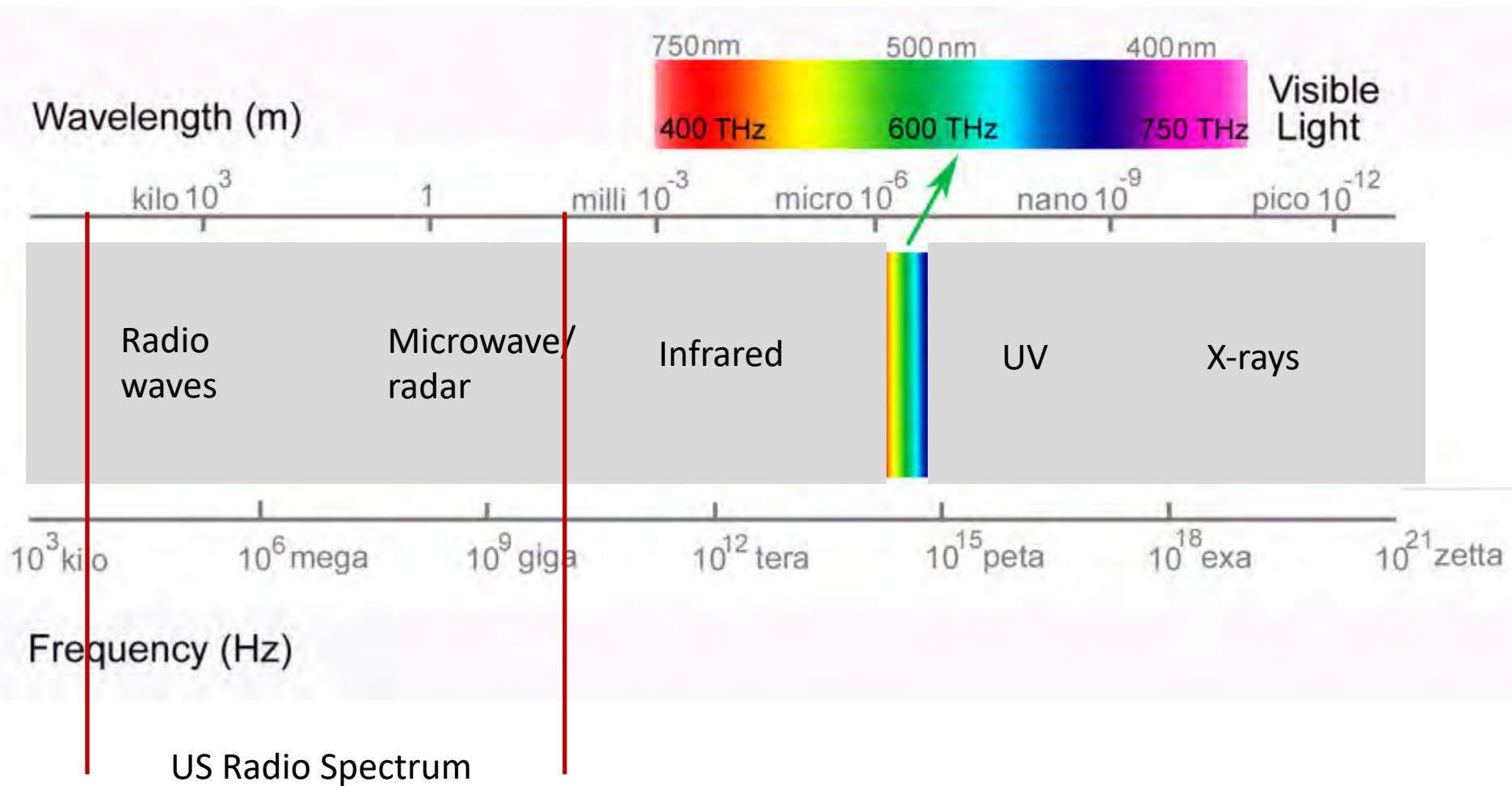
MR3522: Remote Sensing of the Atmosphere and Ocean

The Electromagnetic Spectrum in Earth's Atmosphere

Main topics

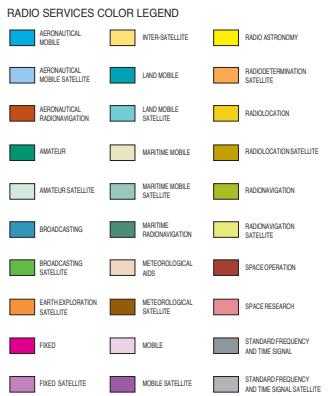
- Types of EM Radiation
- Radio frequency spectrum

Electromagnetic spectrum



UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

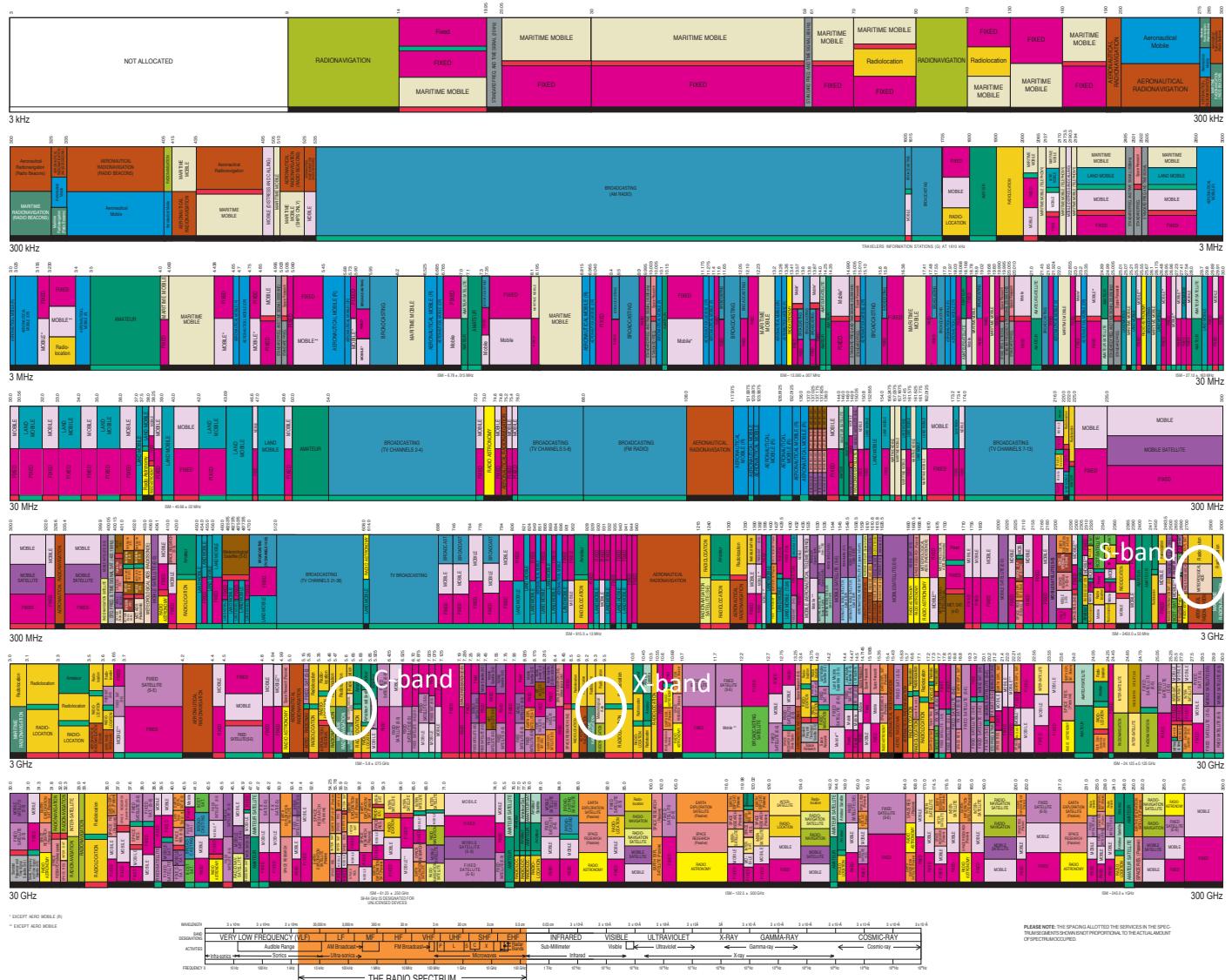


ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital w/ lower case letters

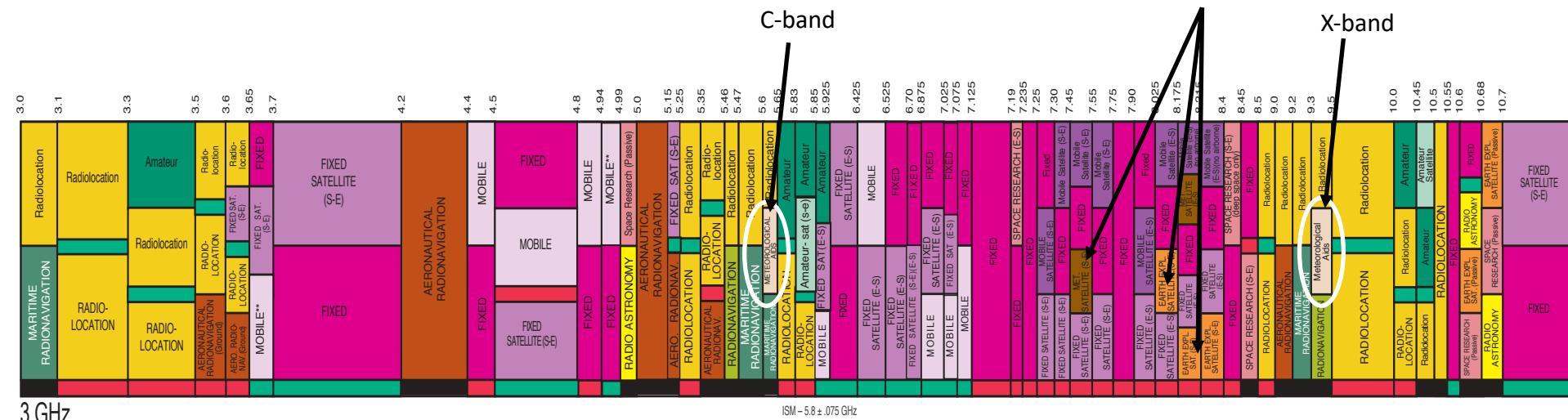
This chart is a graphic single-line portrait of the Table of Frequency Allocations used by the FCC and NTIA. As such, it does not completely reflect all aspects, i.e., licenses and recent changes made to the Table. For more detailed information, or complete information, users should consult the Table to determine the current status of U.S. allocations.

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
October 2003



Full table: <https://transition.fcc.gov/oet/spectrum/table/fccitable.pdf>

Other meteorological/earth exploration satellites



Full table: <https://transition.fcc.gov/oet/spectrum/table/fccitable.pdf>

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Absorption and Scattering in the Atmosphere

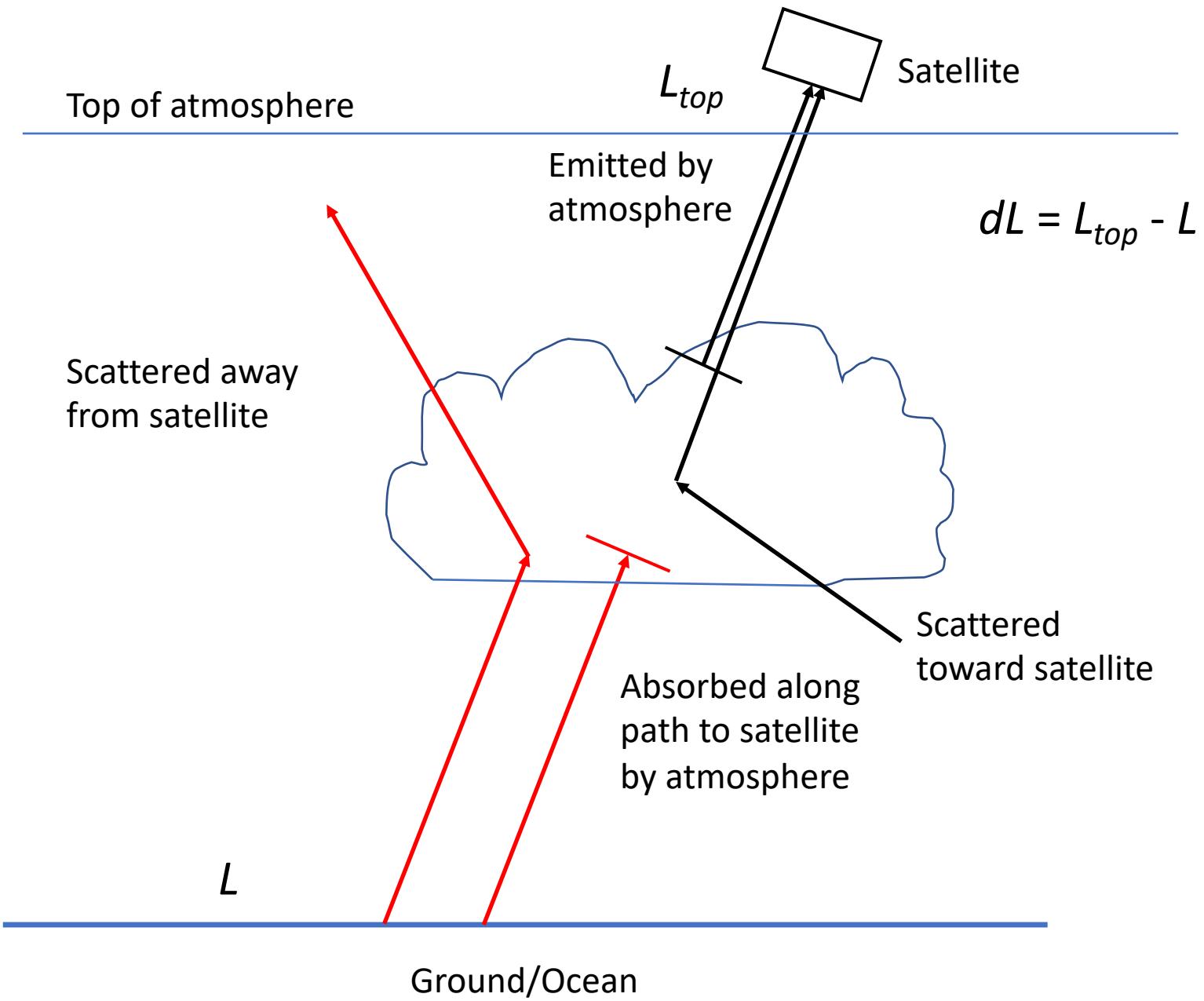
Main Topics

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

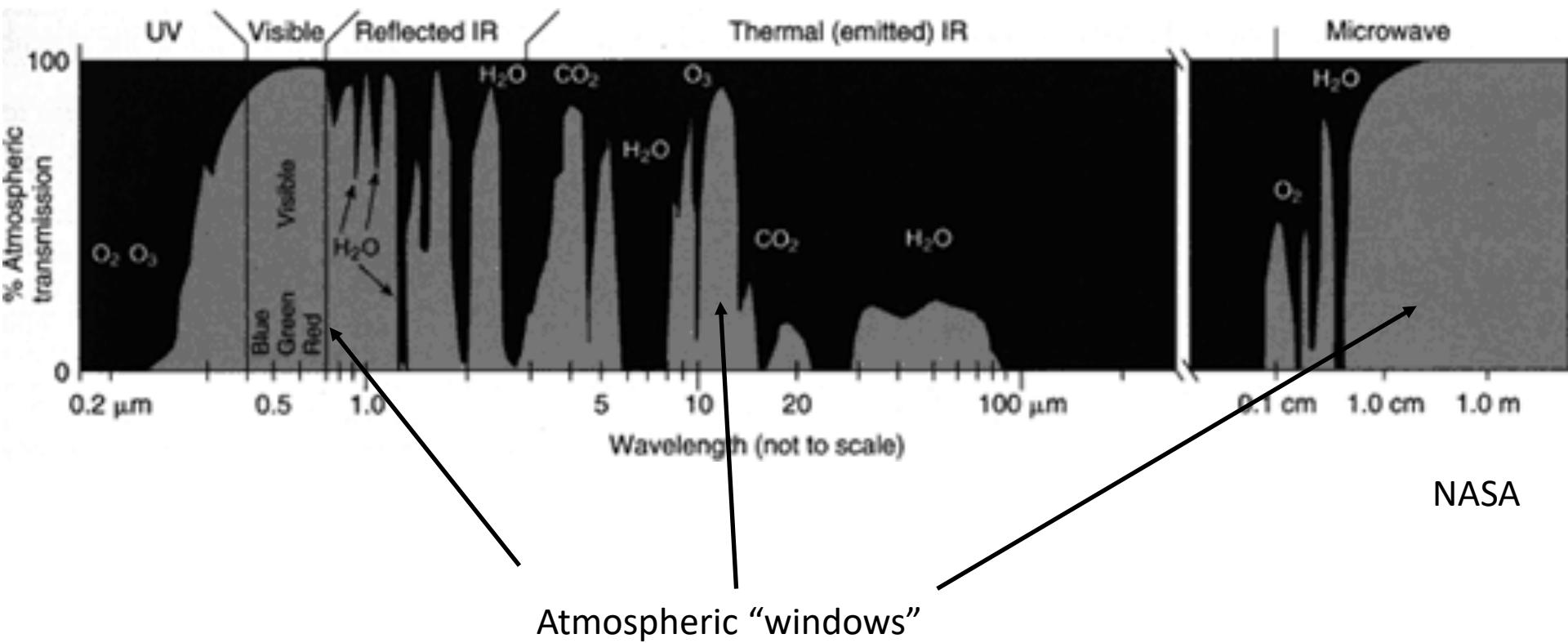
What do satellite instruments measure?
Radiance at some frequency/wavelength at the
top of the atmosphere (TOA)

What are the sources of observed radiation?
Scattering and Emission

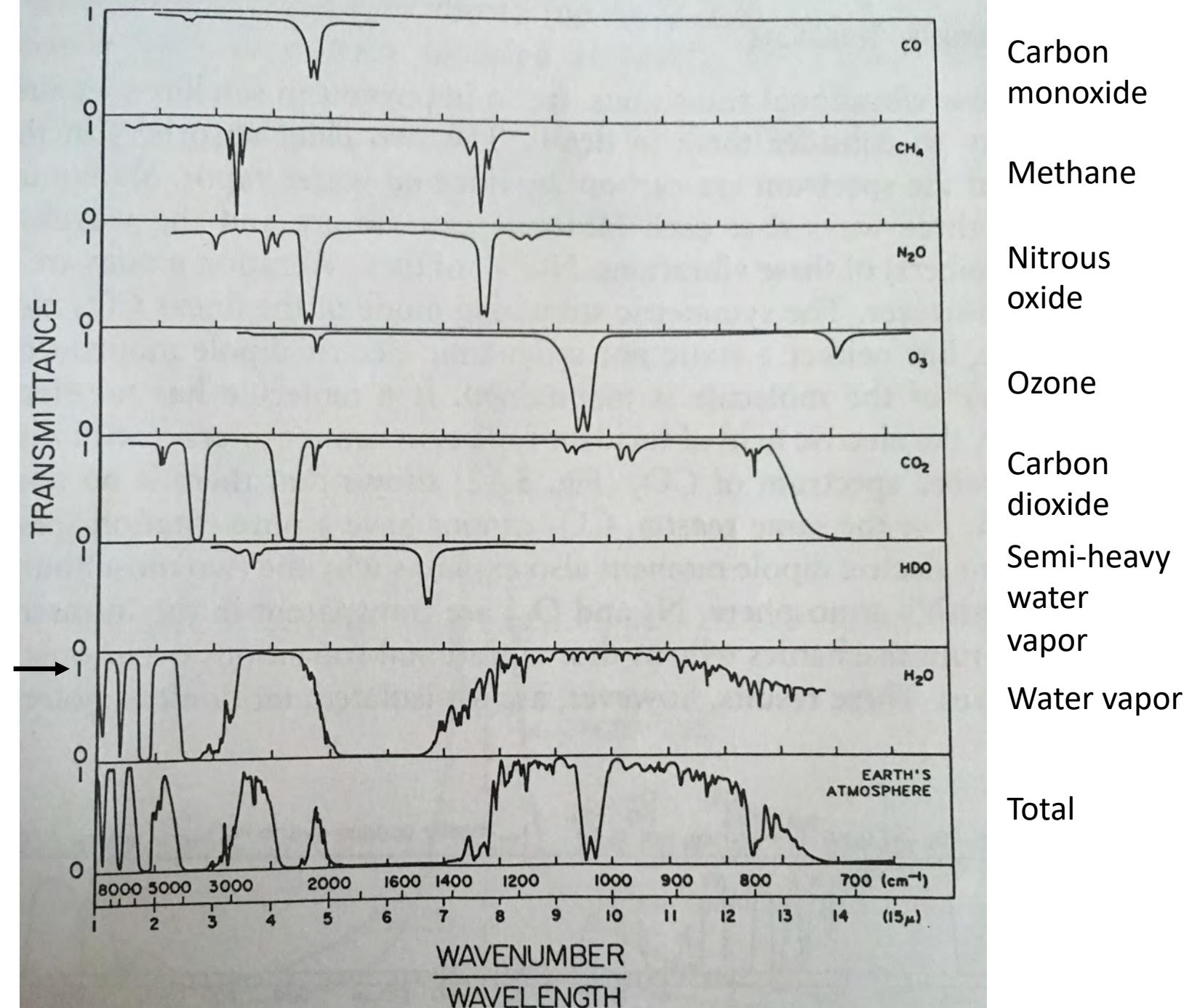
What prevents radiation from reaching the top
of the atmosphere? **Scattering and Absorption**



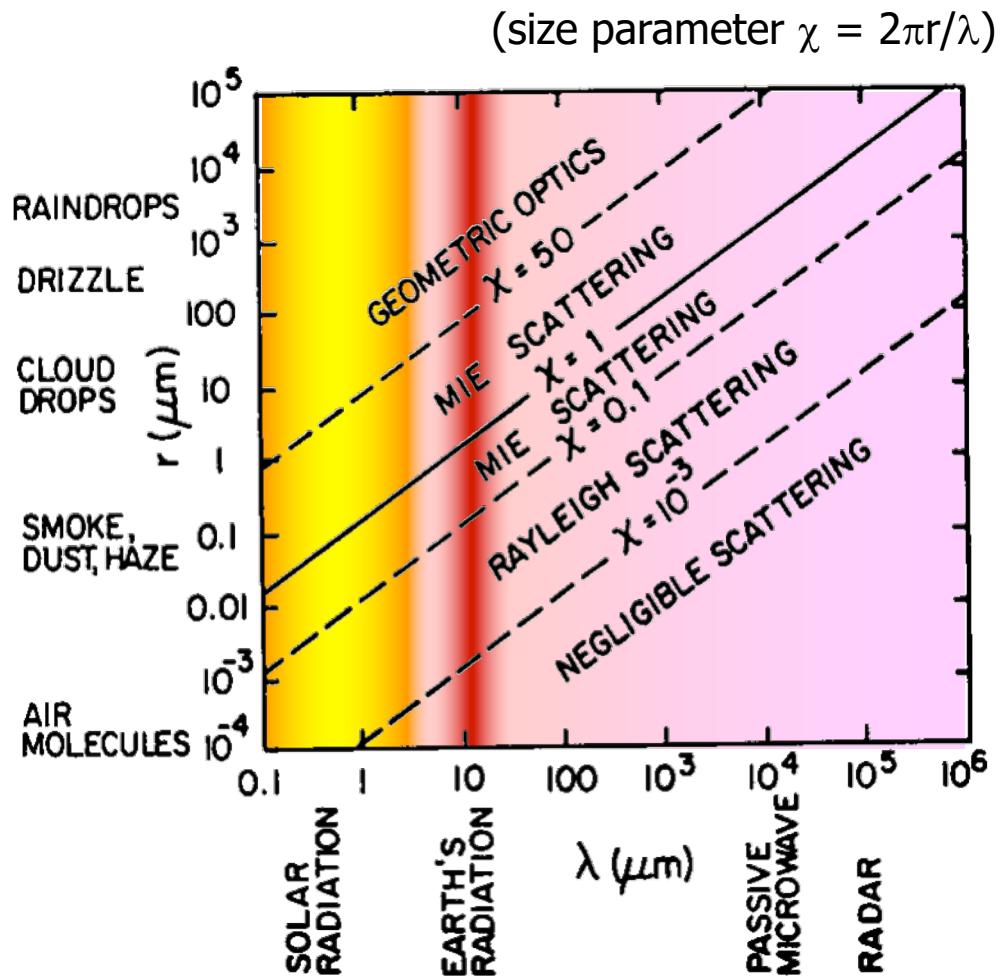
Atmospheric Transmission Spectra



Transmission spectra for common absorbing atmospheric constituents in IR



Scattering in Earth's Atmosphere



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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.

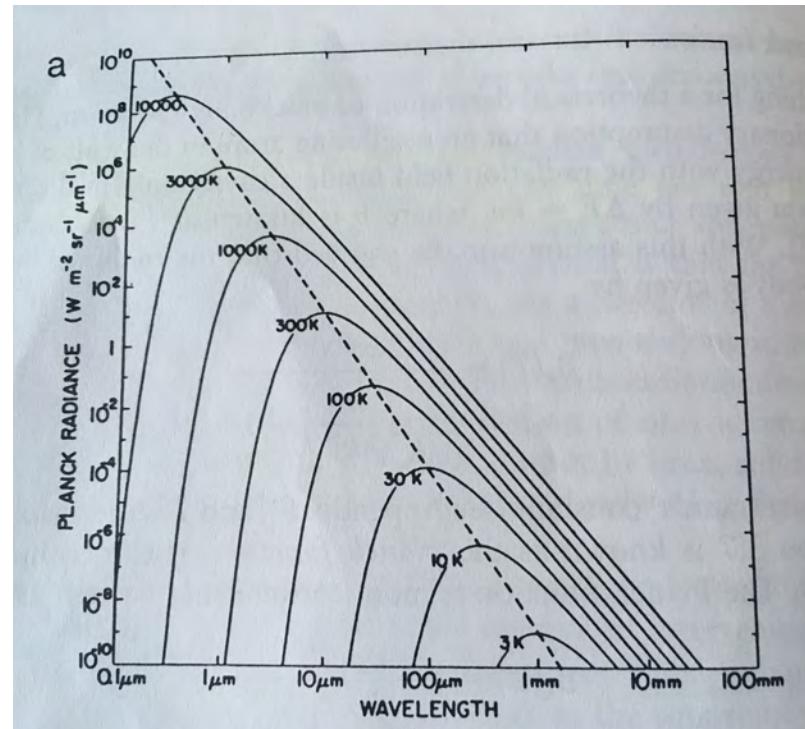
Planck function: $B_\lambda(T) = \frac{2\hbar c^2 \lambda^{-5}}{e^{\frac{\hbar c}{\lambda kT}} - 1}$

$$k = 1.38 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$$

$$\hbar = 6.62607004 \times 10^{-34} \text{ m}^2 \text{ kg s}^{-1}$$

$$c = 3 \times 10^8 \text{ m s}^{-1}$$

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



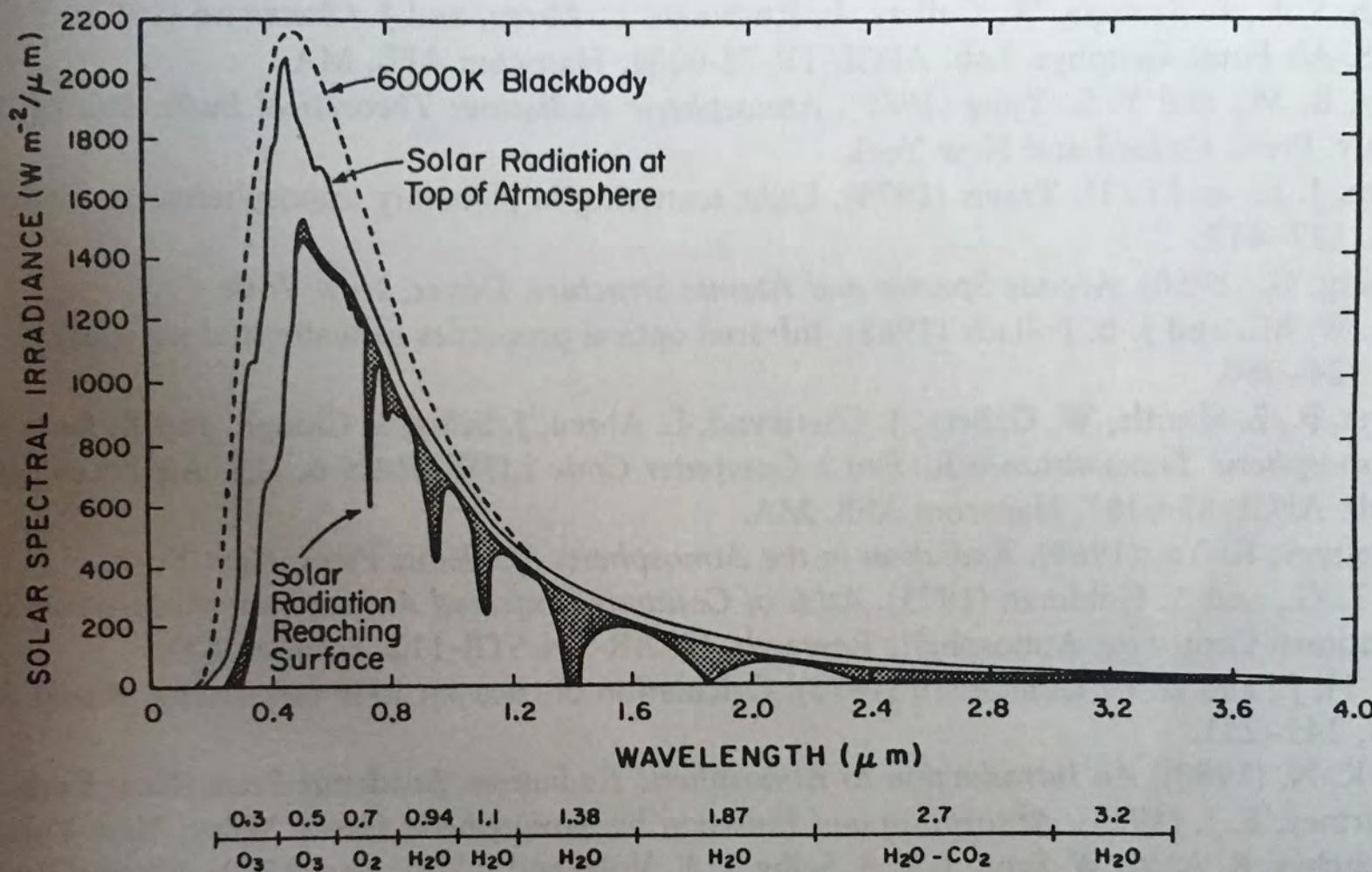


FIGURE 3.23. Solar spectral irradiance. The dashed curve shows the approximate irradiance that would be received at the Earth if the sun were a 6000-K blackbody. The top solid curve shows the spectral irradiance at the top of the atmosphere. (The integral under this curve is the solar constant.) The 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.]

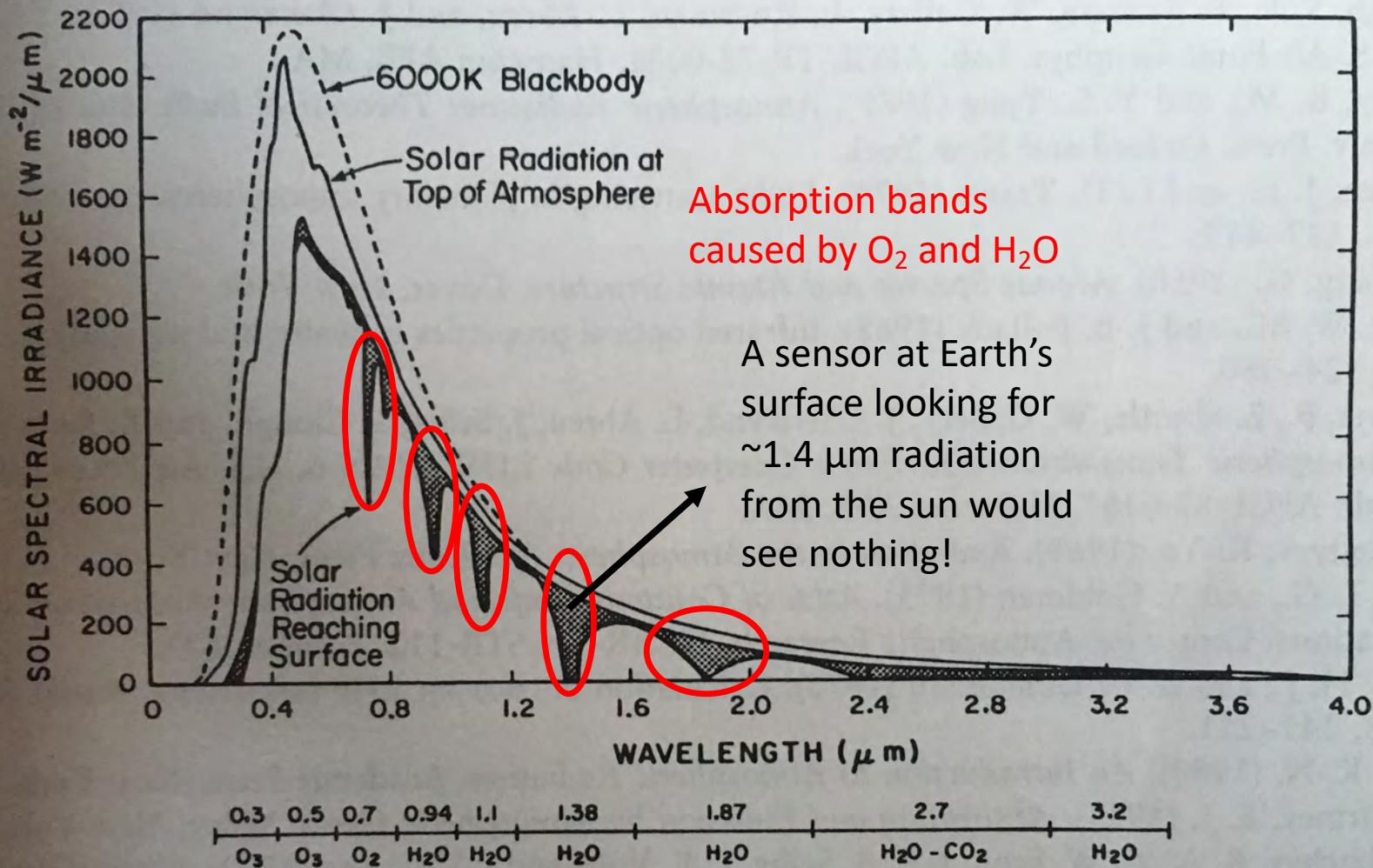


FIGURE 3.23. Solar spectral irradiance. The dashed curve shows the approximate irradiance that would be received at the Earth if the sun were a 6000-K blackbody. The top solid curve shows the spectral irradiance at the top of the atmosphere. (The integral under this curve is the solar constant.) The 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.]

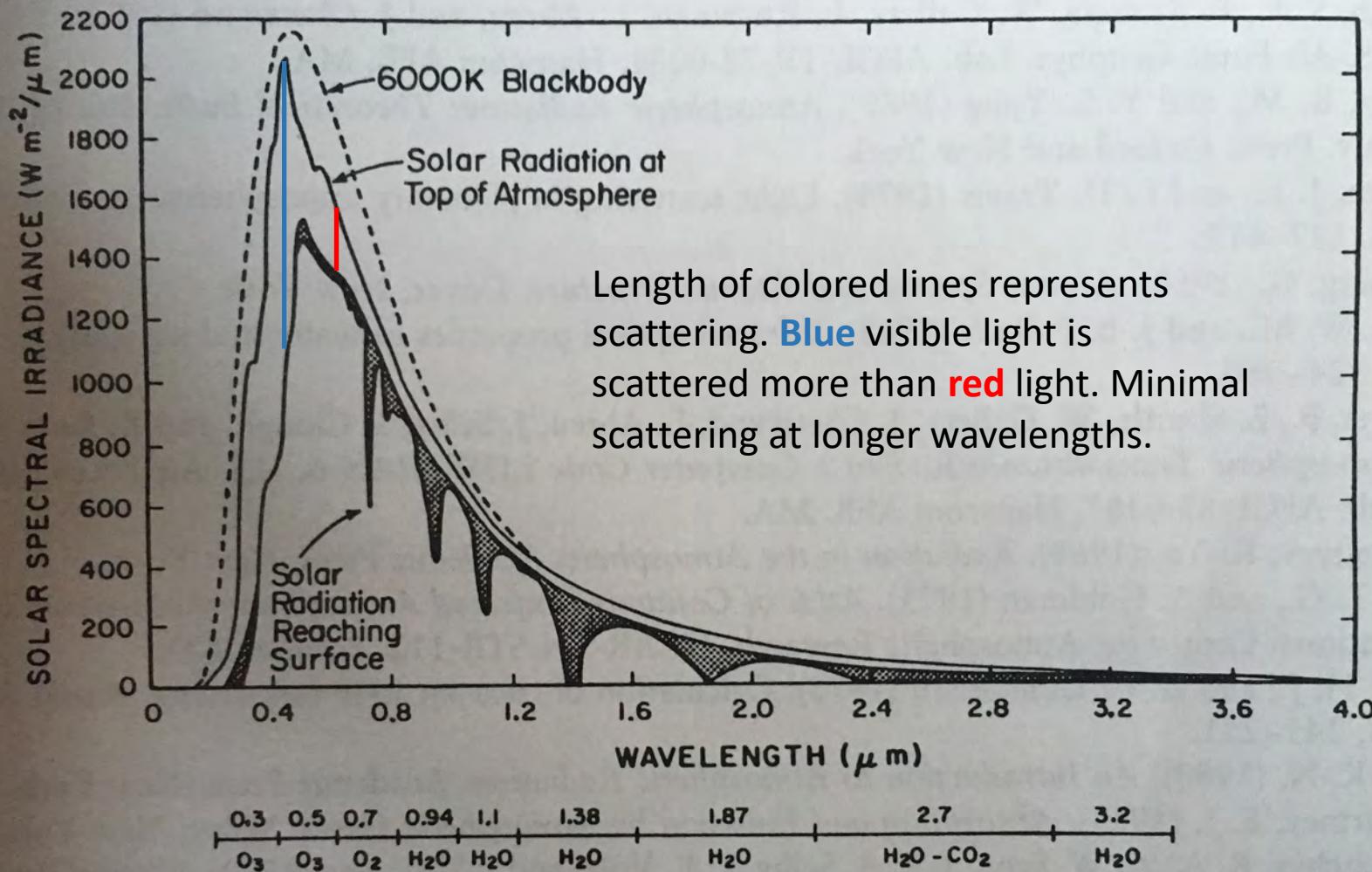
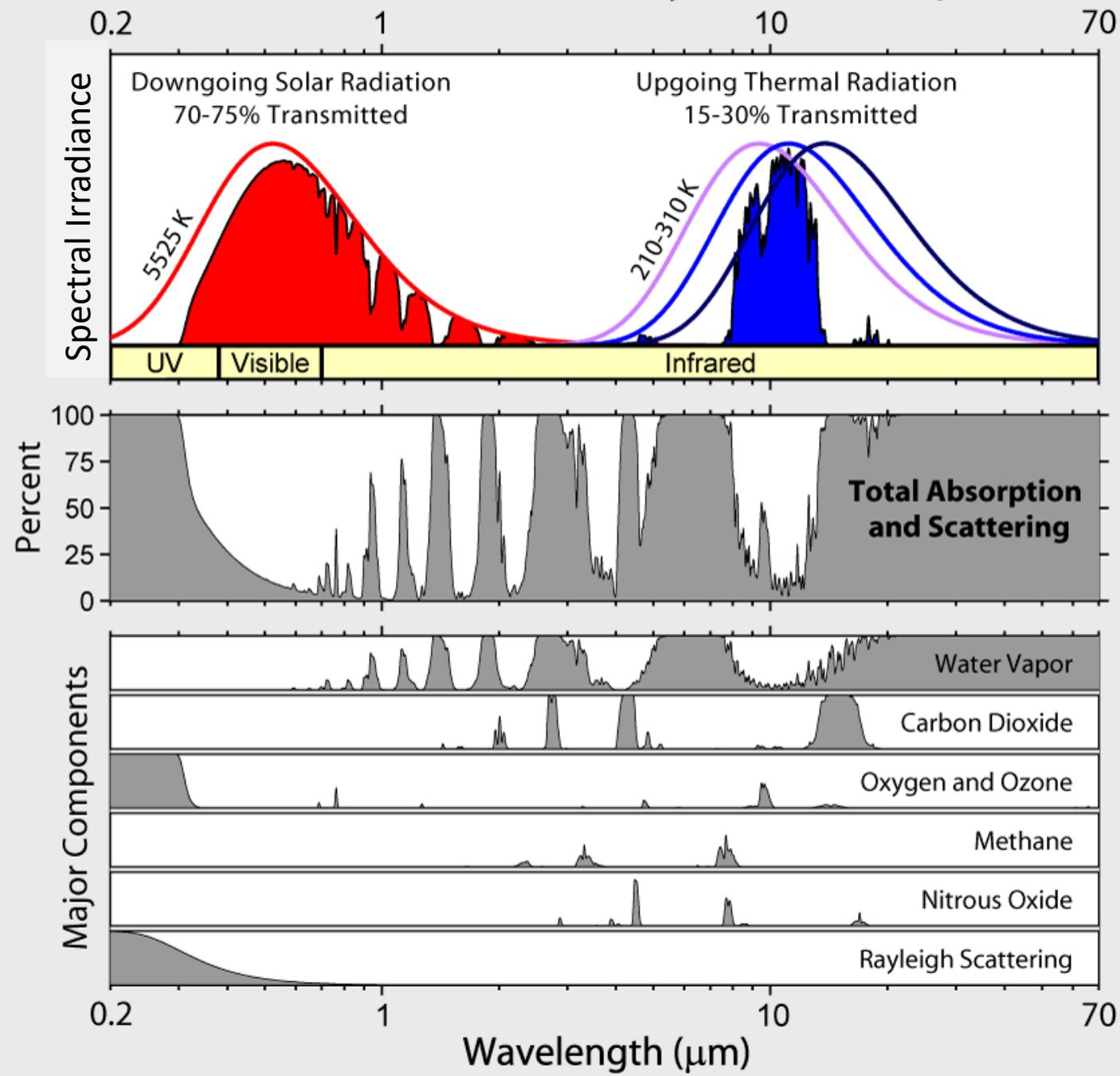


FIGURE 3.23. Solar spectral irradiance. The dashed curve shows the approximate irradiance that would be received at the Earth if the sun were a 6000-K blackbody. The top solid curve shows the spectral irradiance at the top of the atmosphere. (The integral under this curve is the solar constant.) The 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.]

Radiation Transmitted by the Atmosphere



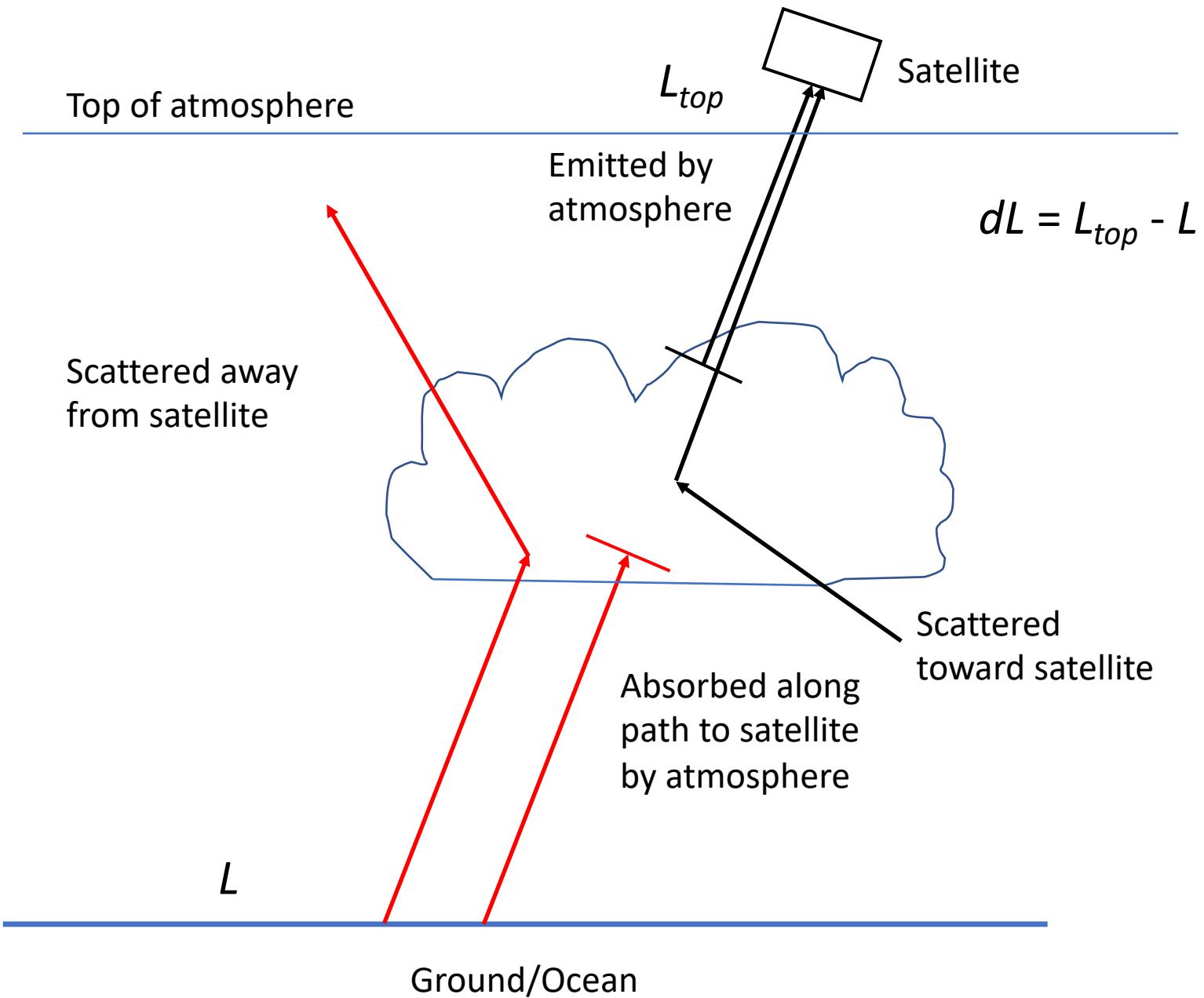
Credit:
Robert
Rohde

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Mathematical Expressions of Radiative Extinction

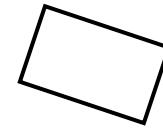
Main Topics

- Schwarzchild's Equation
- Direct transmissivity
- Optical depth



Top of atmosphere

L_{top}



Satellite

$$dL = L_{top} - L$$

At this point X , and
along a path \mathbf{r} toward
the satellite:

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

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

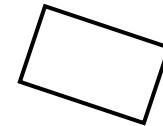
$$dL(X, \mathbf{r}) = -\sigma_{e,\lambda}(X)L_\lambda(X, \mathbf{r}) + J_\lambda(X, \mathbf{r})d\mathbf{r}$$

L

Ground/Ocean

Top of atmosphere

L_{top}



Satellite

$$dL = L_{top} - L$$

At this point X , and
along a path \mathbf{r} toward
the satellite:

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

L

Ground/Ocean

Terms:

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

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

Volume absorption
coefficient

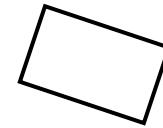
Volume scattering
coefficient

Single
scattering
albedo

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

Top of atmosphere

L_{top}



Satellite

$$dL = L_{top} - L$$

At this point X , and
along a path \mathbf{r} toward
the satellite:

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

L

Terms:

$J_\lambda(X, \mathbf{r})$: Source of radiation

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

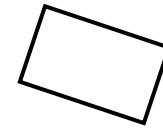
Source from
thermal
emissions

Source from
scattering

Ground/Ocean

Top of atmosphere

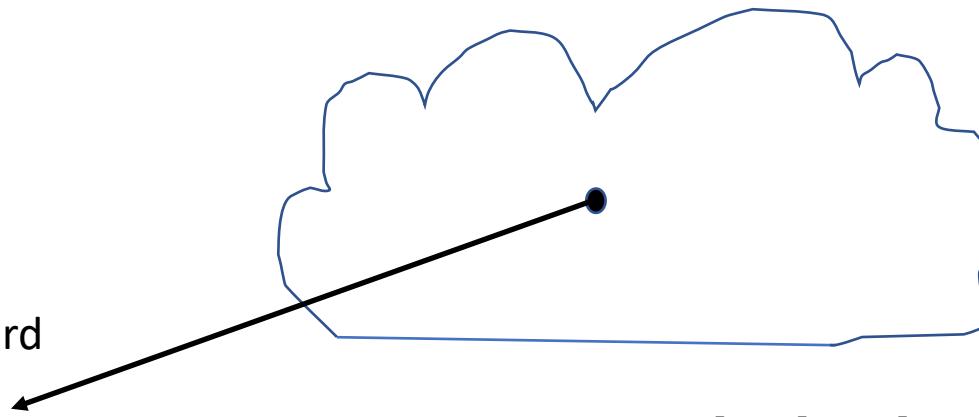
L_{top}



Satellite

$$dL = L_{top} - L$$

At this point X , and
along a path \mathbf{r} toward
the satellite:



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

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

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

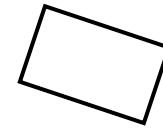
Recall Kirchhoff's Law*: $|\sigma_{a,\lambda}| = \varepsilon_\lambda$

L

Ground/Ocean

Top of atmosphere

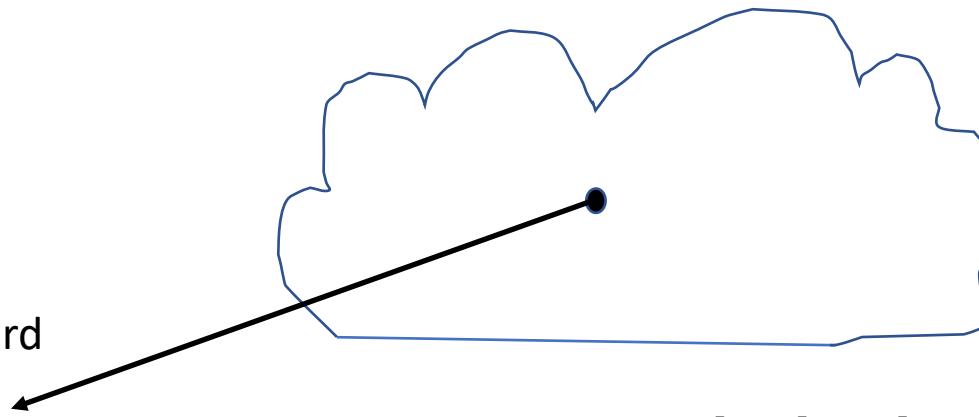
L_{top}



Satellite

$$dL = L_{top} - L$$

At this point X , and
along a path \mathbf{r} toward
the satellite:



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

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

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

L

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

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 ∞ .

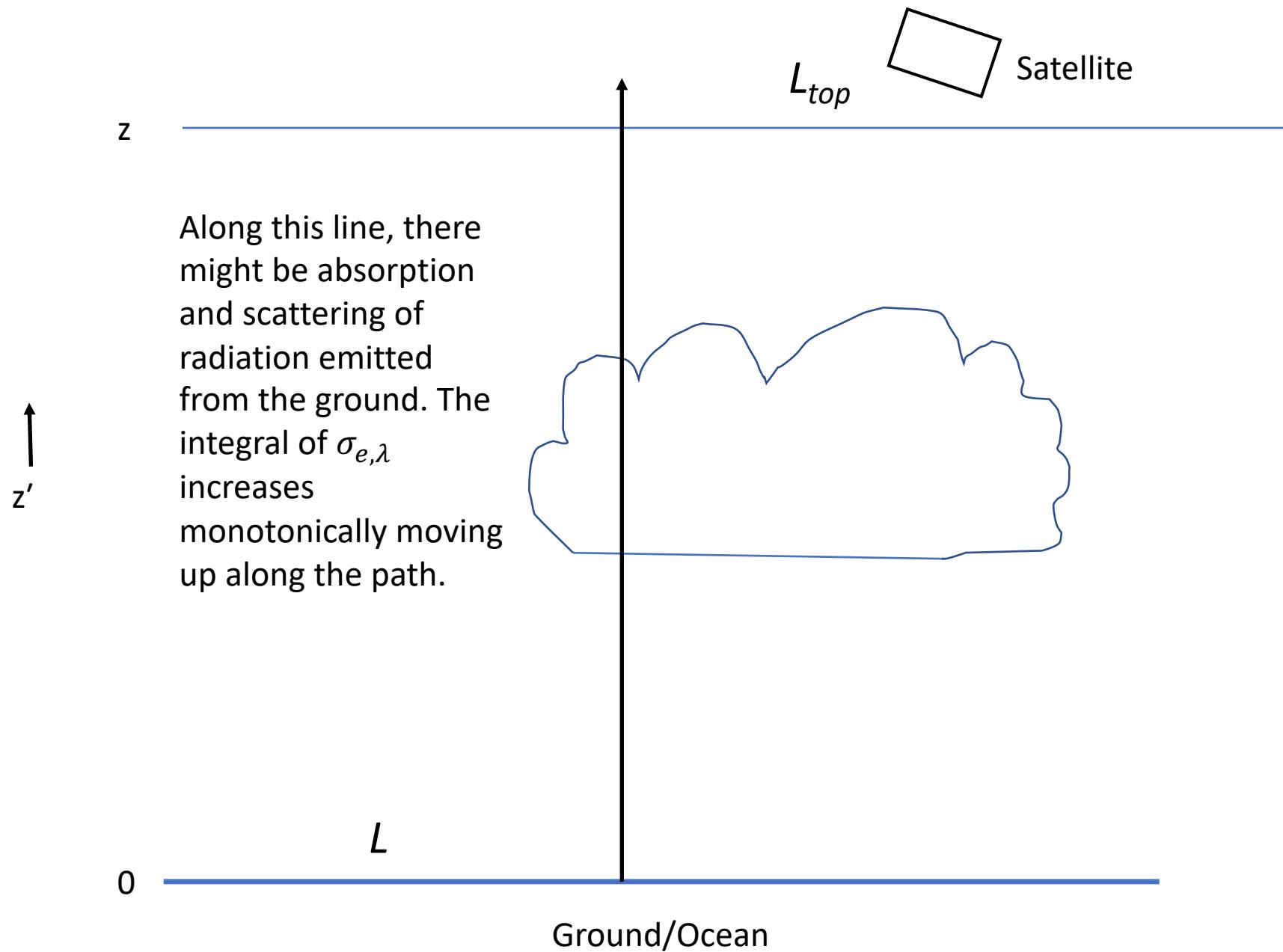
Direct transmittance:

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

$$\mu = \cos \theta$$

θ is the slant path angle of radiation

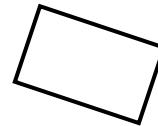
Path optical depth (regardless of whether the path is vertical) is then $\delta_\lambda(s) = \int_{s_1}^{s_2} \sigma_{e,\lambda}(s') ds'$ in which s' is the coordinate along the path (which is just z' if the path is vertical).



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

z

L_{top}



Satellite

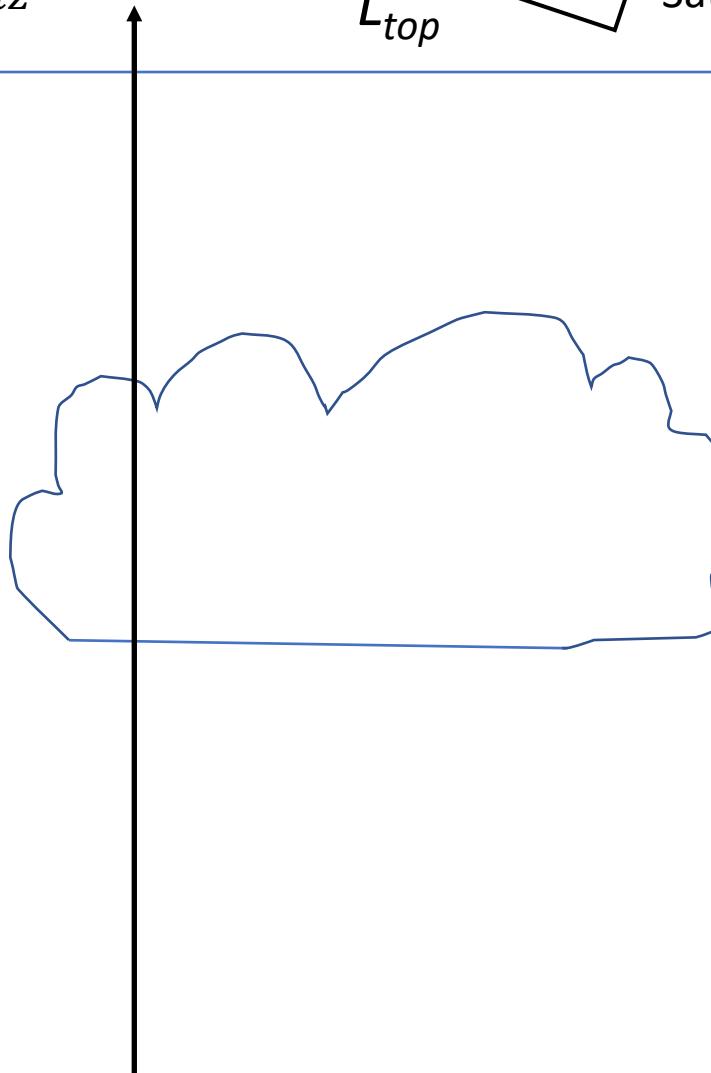
Along this line, there might be absorption and scattering of radiation emitted from the ground. The integral of $\sigma_{e,\lambda}$ increases monotonically moving up along the path.

$\uparrow z'$

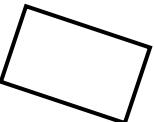
L

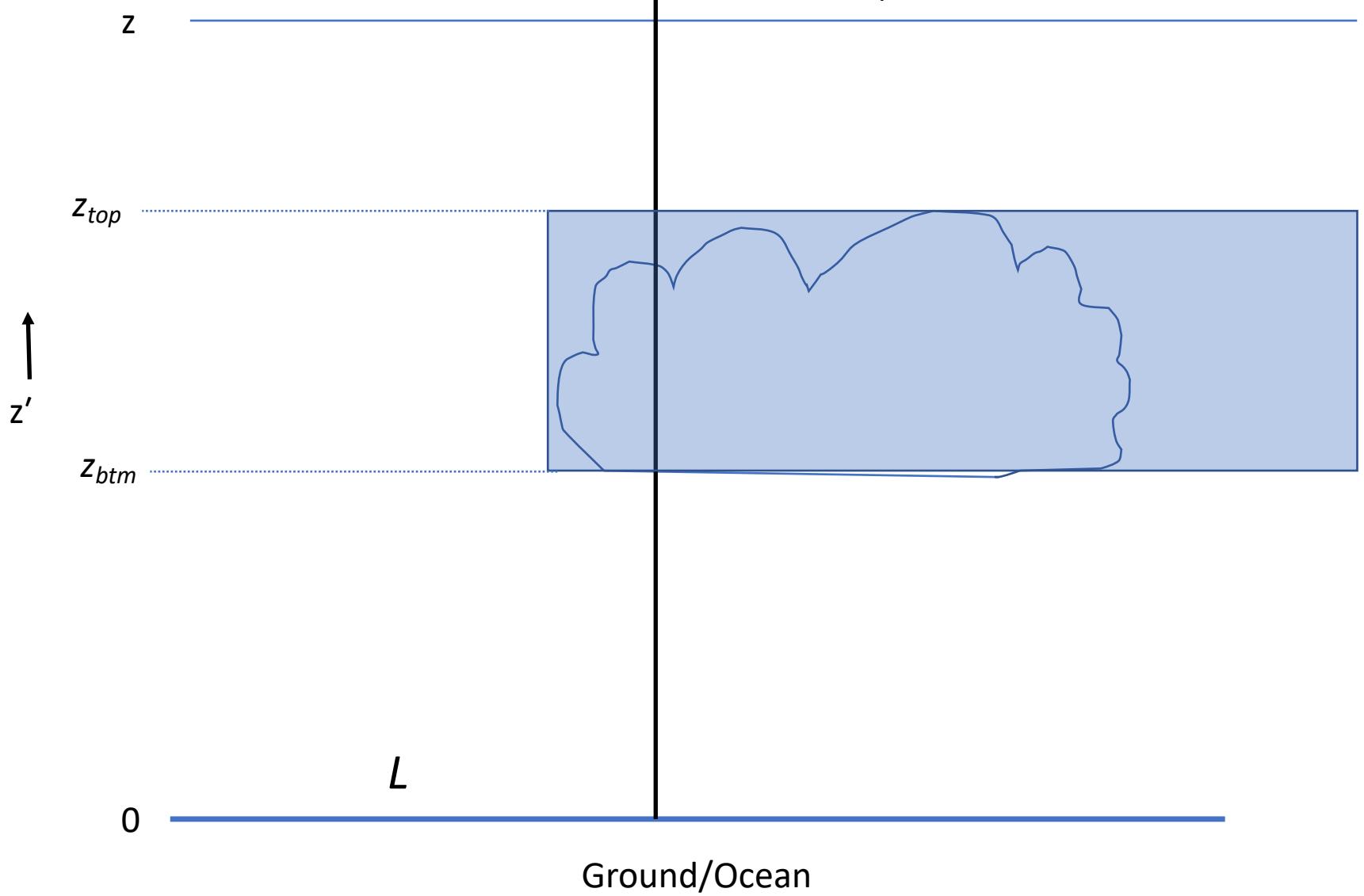
0

Ground/Ocean



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

L_{top}  Satellite



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

z

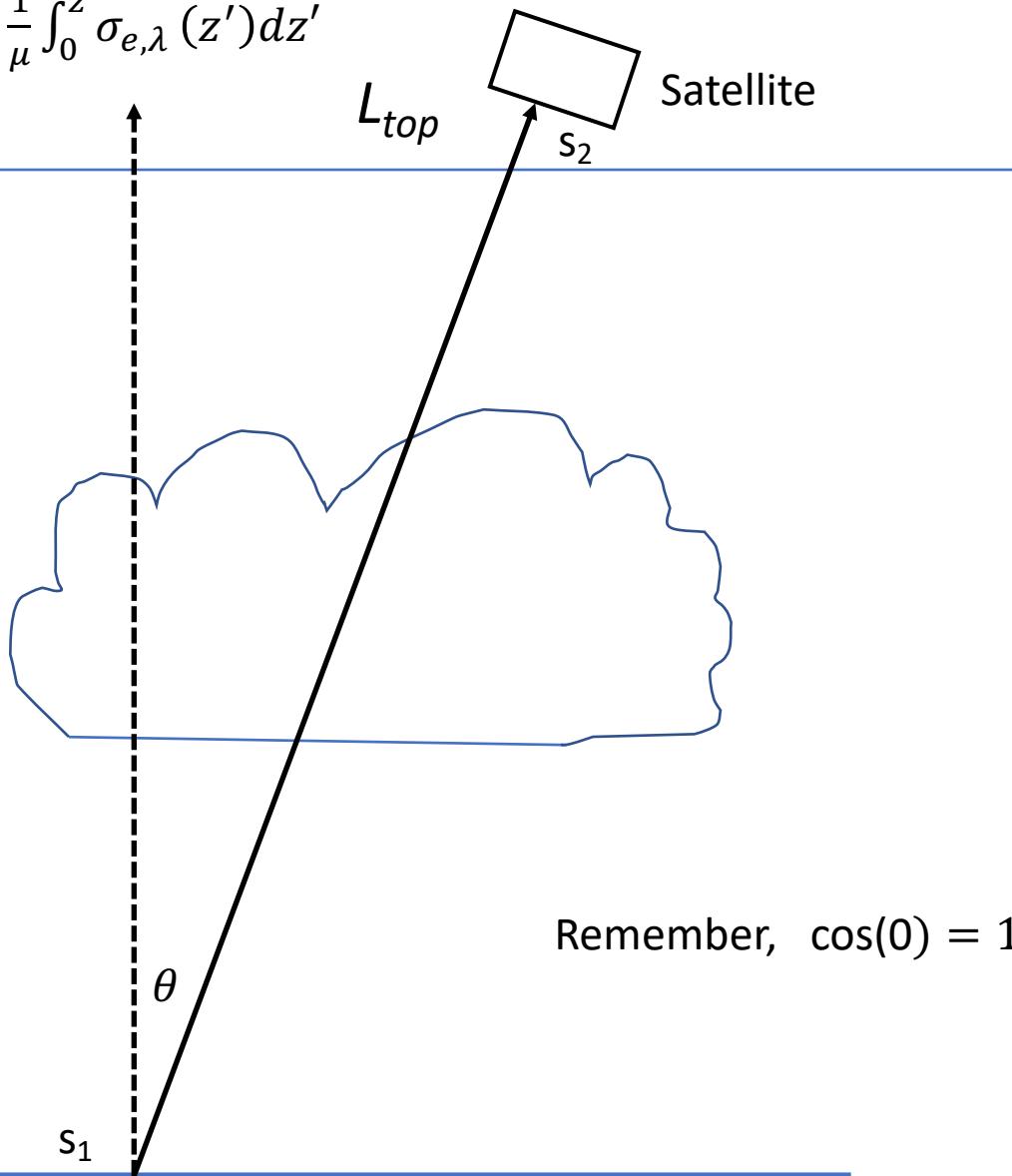
$\uparrow z'$

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.

0

L

Ground/Ocean



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

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Idealized Expressions of Radiative Transfer

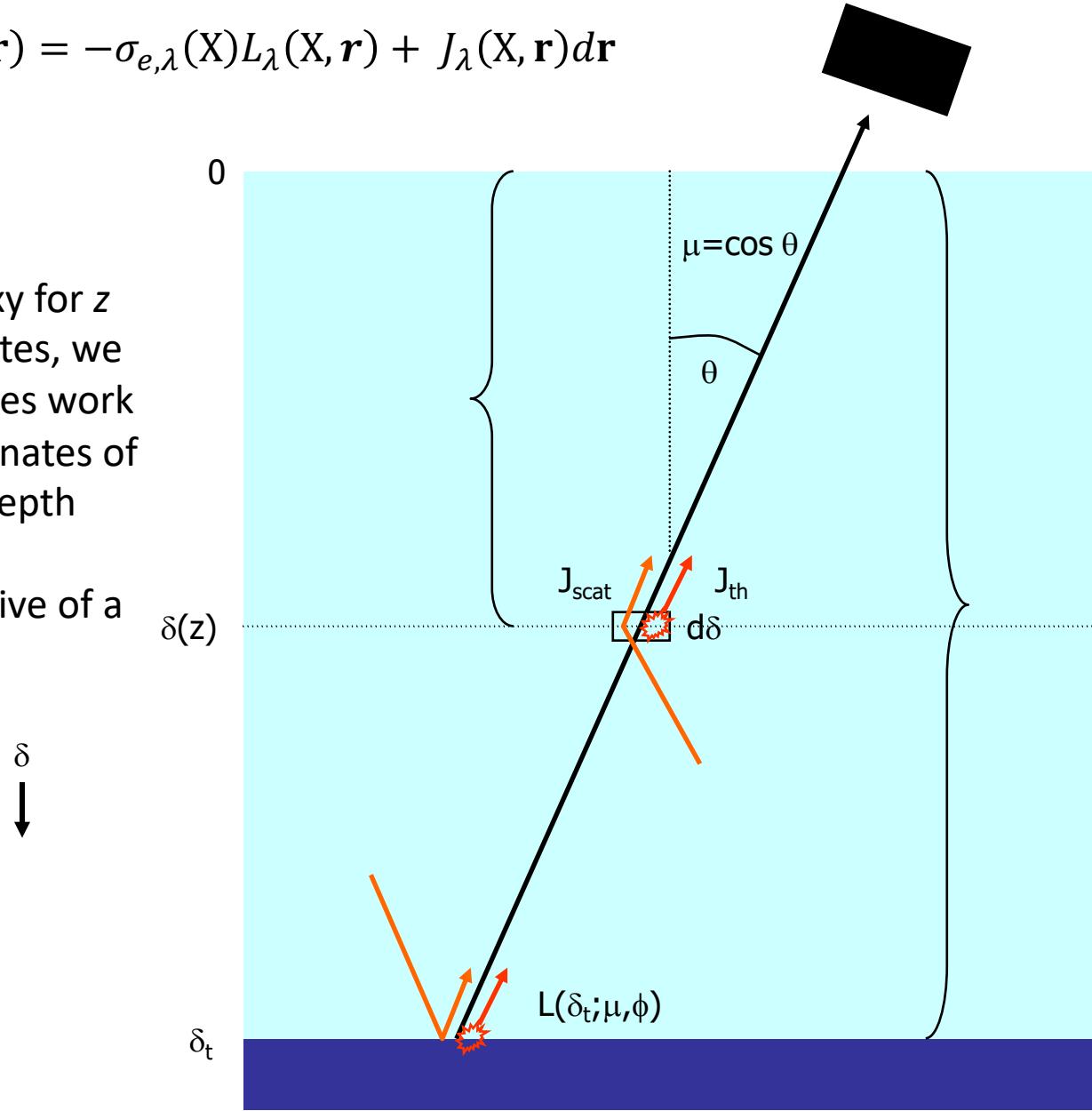
Main Topics

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

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

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

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



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

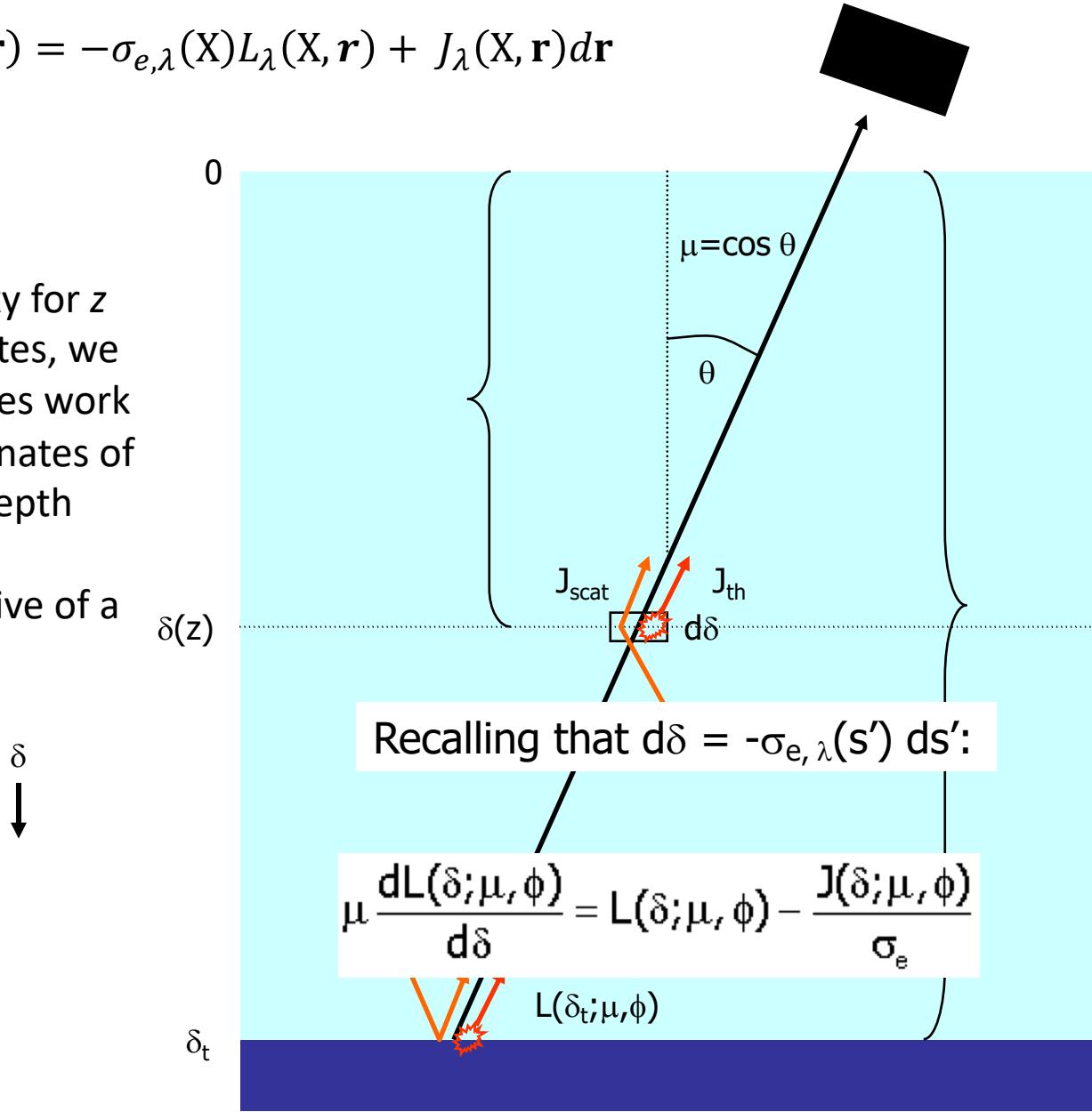
The path through the atmosphere is longer than a vertical path, so the path optical depth is larger than the optical depth of the atmosphere.

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

$$\mu = \cos \theta$$

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

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.

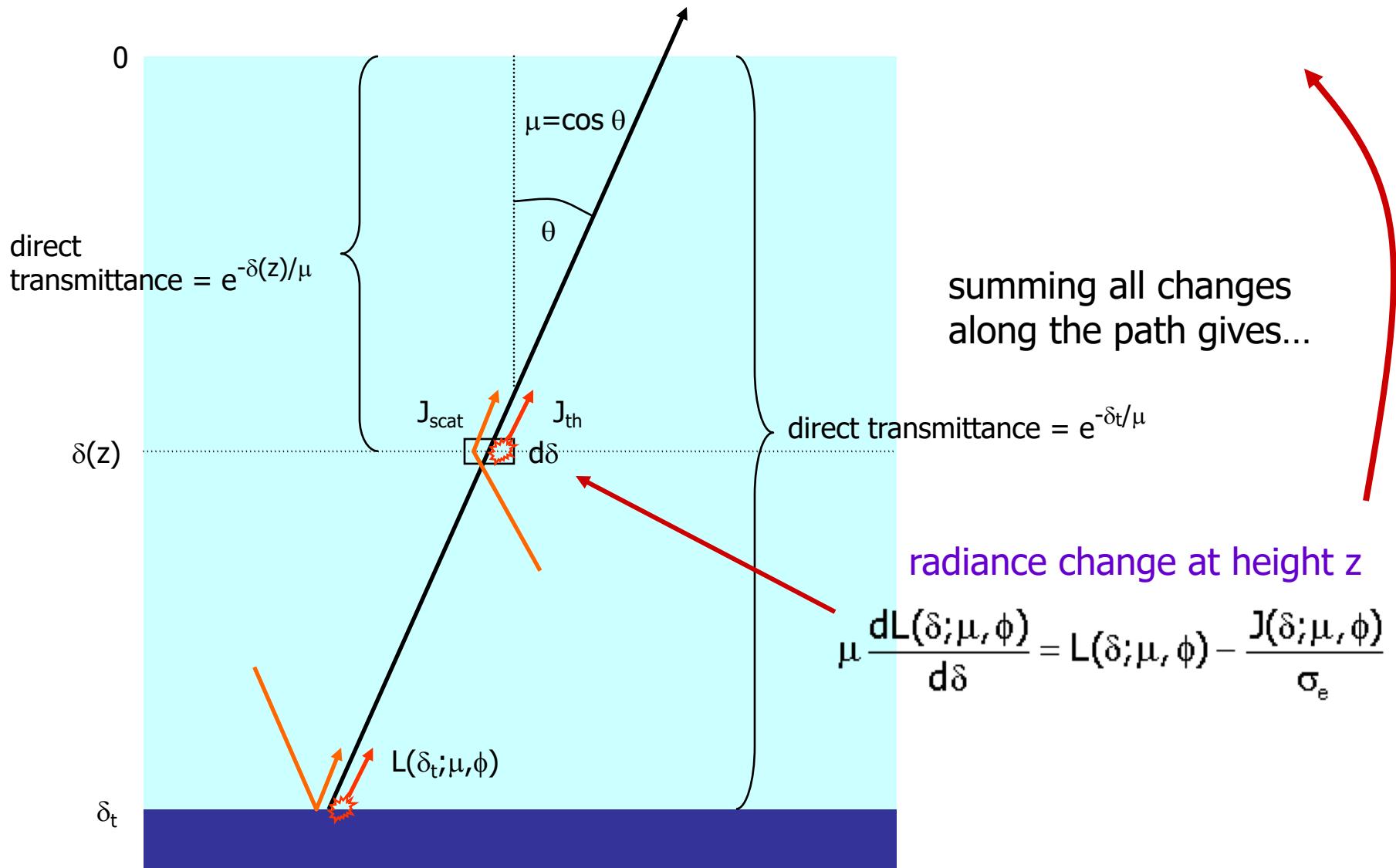
$$\delta_\lambda(s) = \frac{\delta_\lambda(z)}{\mu}$$

$$\mu = \cos \theta$$

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

General solution at top of atmosphere:

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

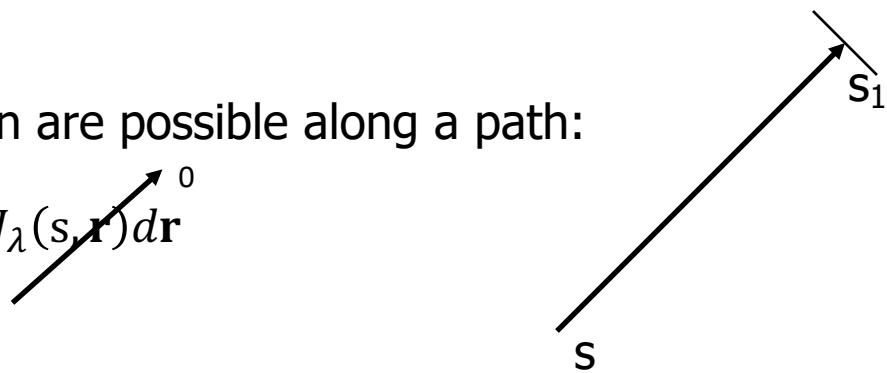


Beer-Lambert-Bouguer Law

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

$$dL(s, \mathbf{r}) = -\sigma_{e,\lambda}(s)L_\lambda(s, \mathbf{r}) + J_\lambda(s, \mathbf{r})dr^0$$

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



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

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

Optical depth
along an arbitrary
path from s to s₁:

$$\delta(s) = \int_s^{s_1} \sigma_e(s')ds'$$

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

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 s₁

Idealized Case #1

No Path Radiance

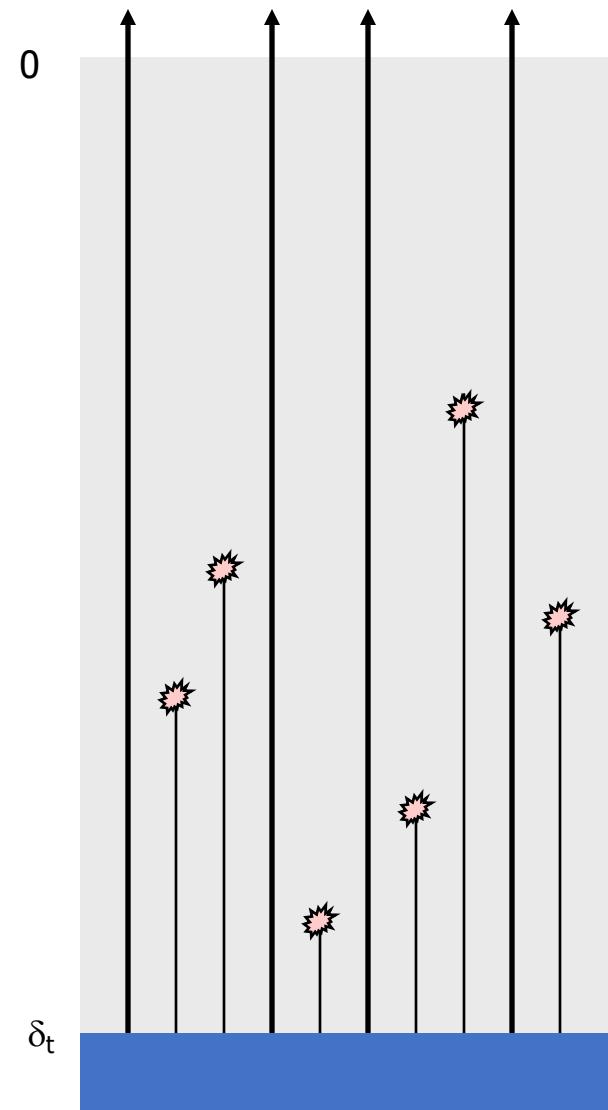
We are at a wavelength where $B(\lambda, T) \sim 0$
and there is **no scattering** into the beam

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

if $\theta = 0$

$$\delta_t = \quad 0.01 \quad 0.1 \quad 1.0 \quad 7$$

$$e^{-\delta_t} = \quad 99\% \quad 90.5\% \quad 36.8\% \quad 0.1\%$$

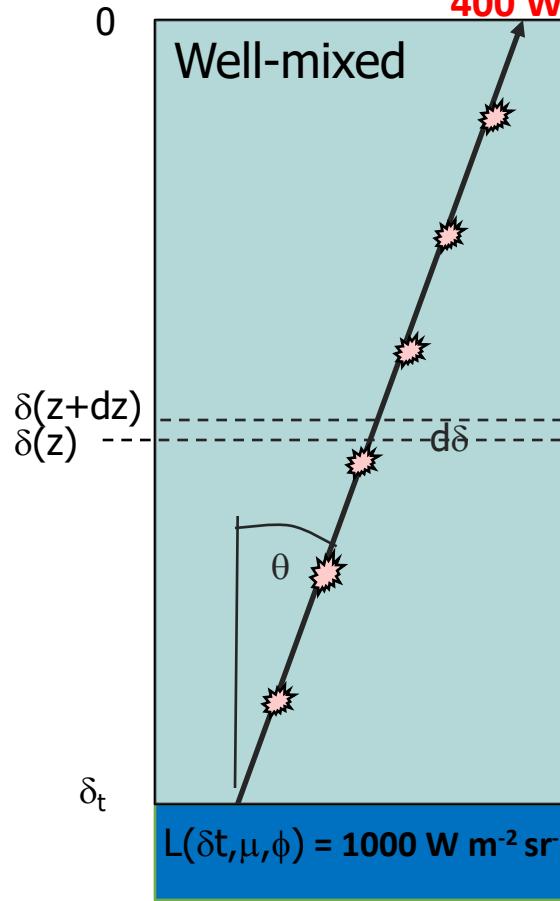


Radiance measured at the top of the atmosphere, $L(0)$, is the same in all three

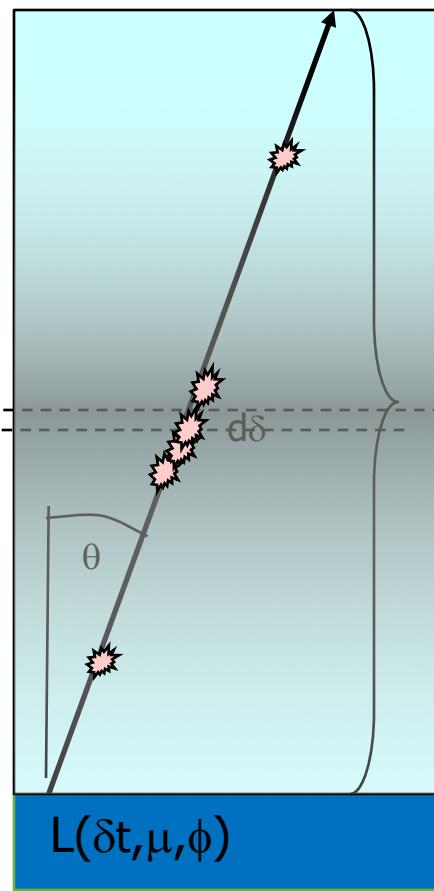
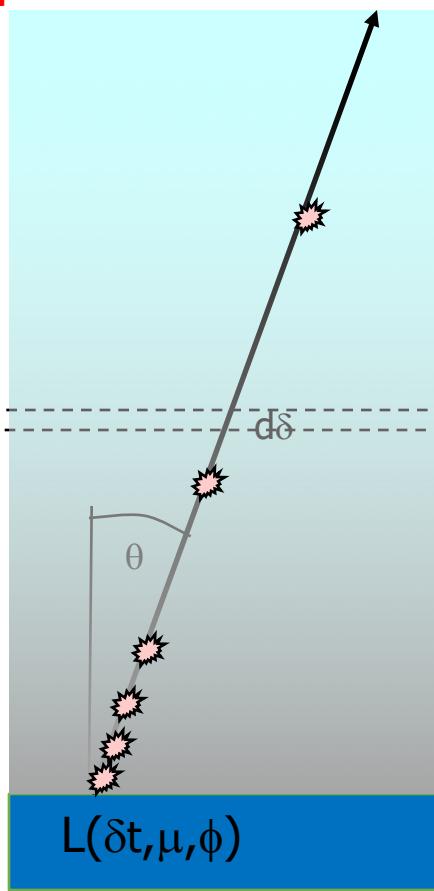
What is δ ?

Suppose $\theta = 30^\circ$

$$\mu = \cos \theta$$



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



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

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

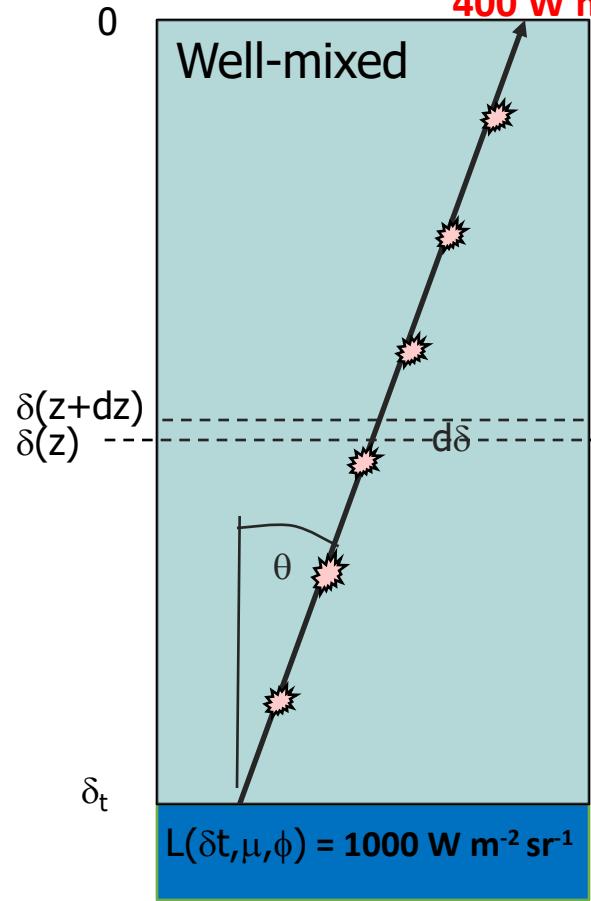
Radiance measured at the top of the atmosphere, $L(0)$, is the same in all three

$$\delta \sim 0.79$$

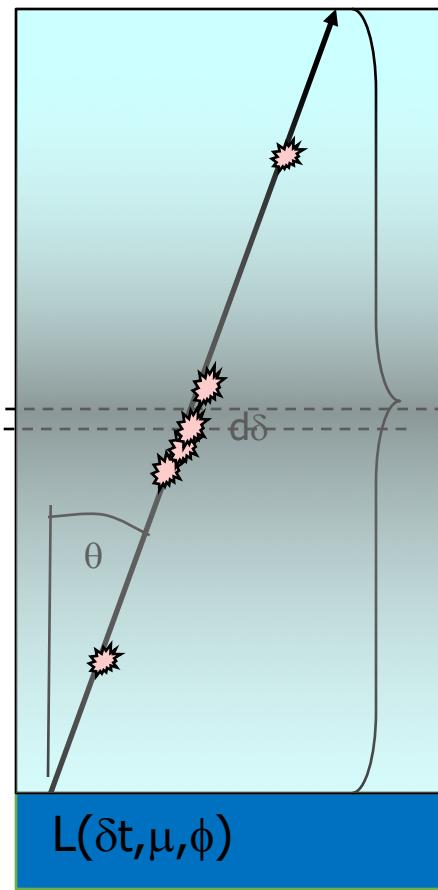
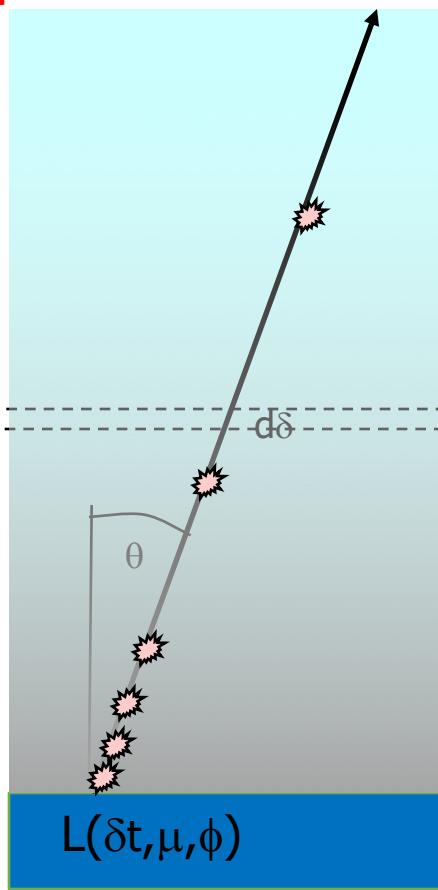
Suppose $\theta = 30^\circ$

$$\mu = \cos \theta$$

$$400 \text{ W m}^{-2} \text{ sr}^{-1}$$



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



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 $\sigma_e = \sigma_a$.

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

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



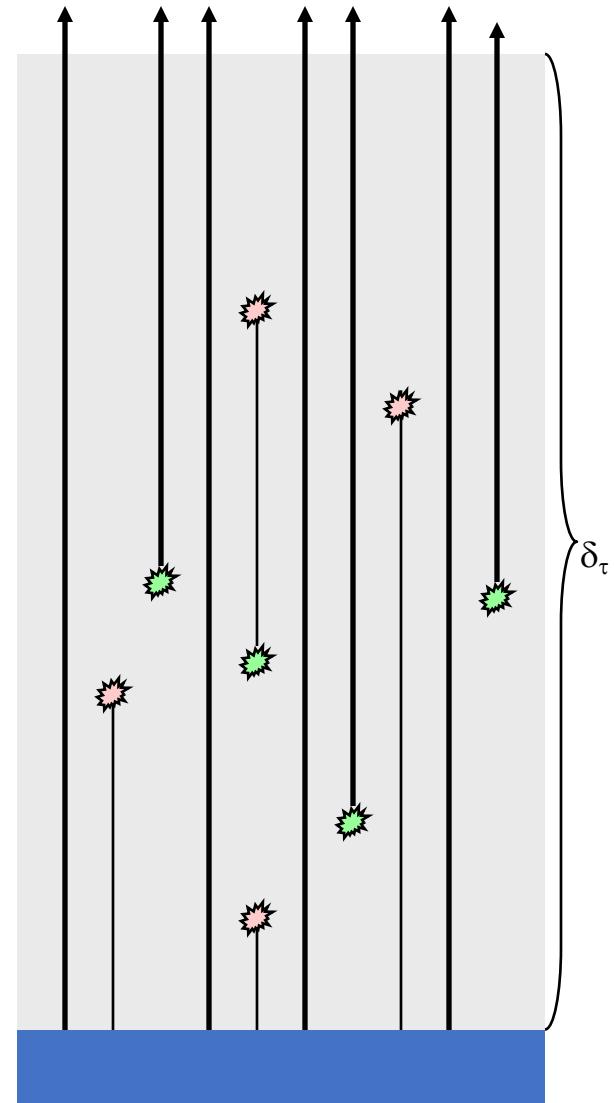
Kirchhoff's Law

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

Direct
transmittance
across path

Direct
transmittance
along path
from δ'

Emitted
radiance by
surface

Emission along
path

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

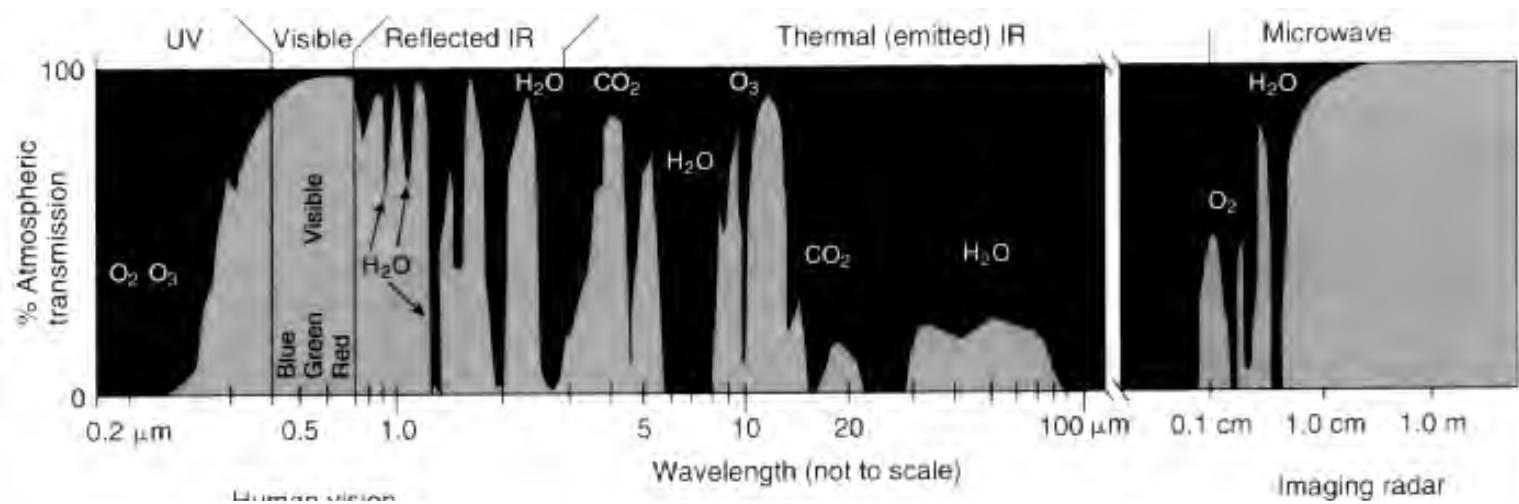
1

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)

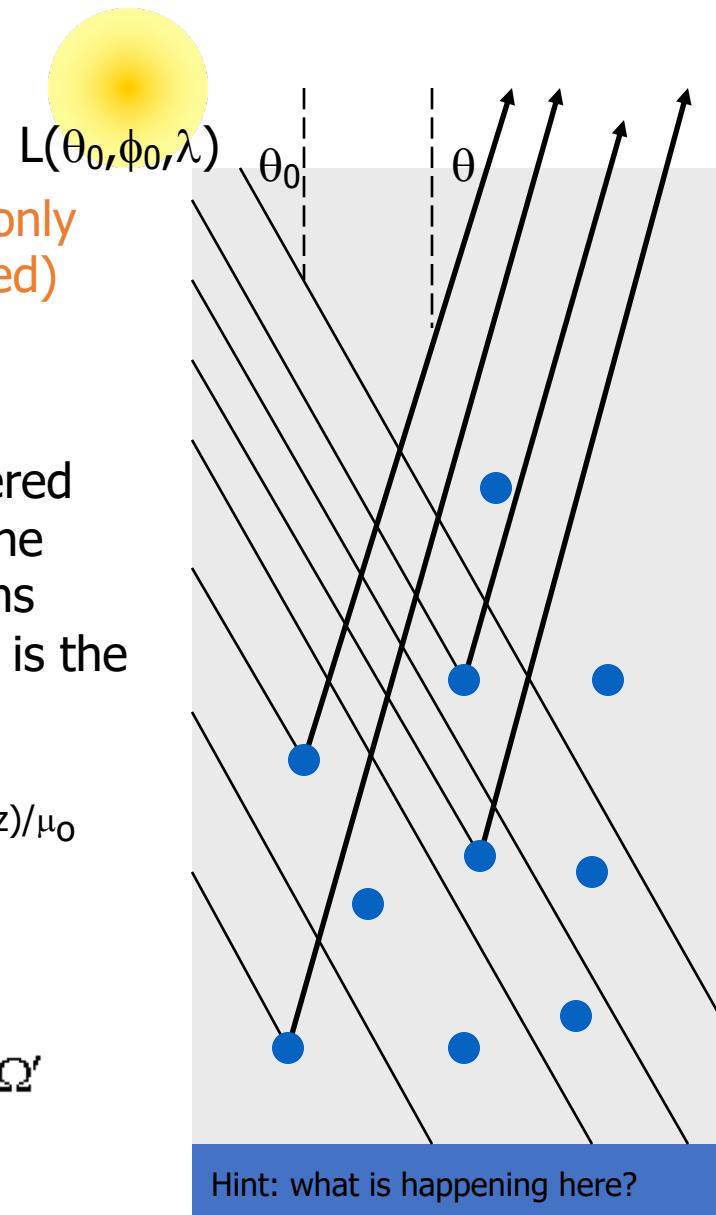
$$J = J_{\text{scat}} \text{ only} \quad \mu_0 = \cos \theta_0$$

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:

$$L(\mathbf{r}', \lambda, \mathbf{X}) = L(\theta_0, \phi_0, \lambda, \mathbf{X}) = L(\theta_0, \phi_0, \lambda) e^{-\delta(\lambda, z)/\mu_0}$$

The path radiance is then

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



Hint: what is happening here?

At the top of the atmosphere the result is...

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

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

If we apply this to a single homogeneous layer...

$$L_t(\lambda, \theta, \phi) = L_0(\lambda, \theta, \phi) e^{-\delta(\lambda)/\mu} + \frac{\omega_0(\lambda) p(\psi_s, \lambda)}{4\pi} L(\theta_0, \phi_0; \lambda) \underbrace{\int_0^{\delta(\lambda)} e^{-\delta(\lambda, z)(1/\mu+1/\mu_0)} \frac{d\delta}{\mu}}_{\text{Probability of a scattering interaction (rather than an absorption)}}$$

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

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

Radiance scattered off the surface toward satellite

Probability of a scattering interaction (rather than an absorption)

Radiance entering the top of the layer

Probability of transmitting through the atmosphere.

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.

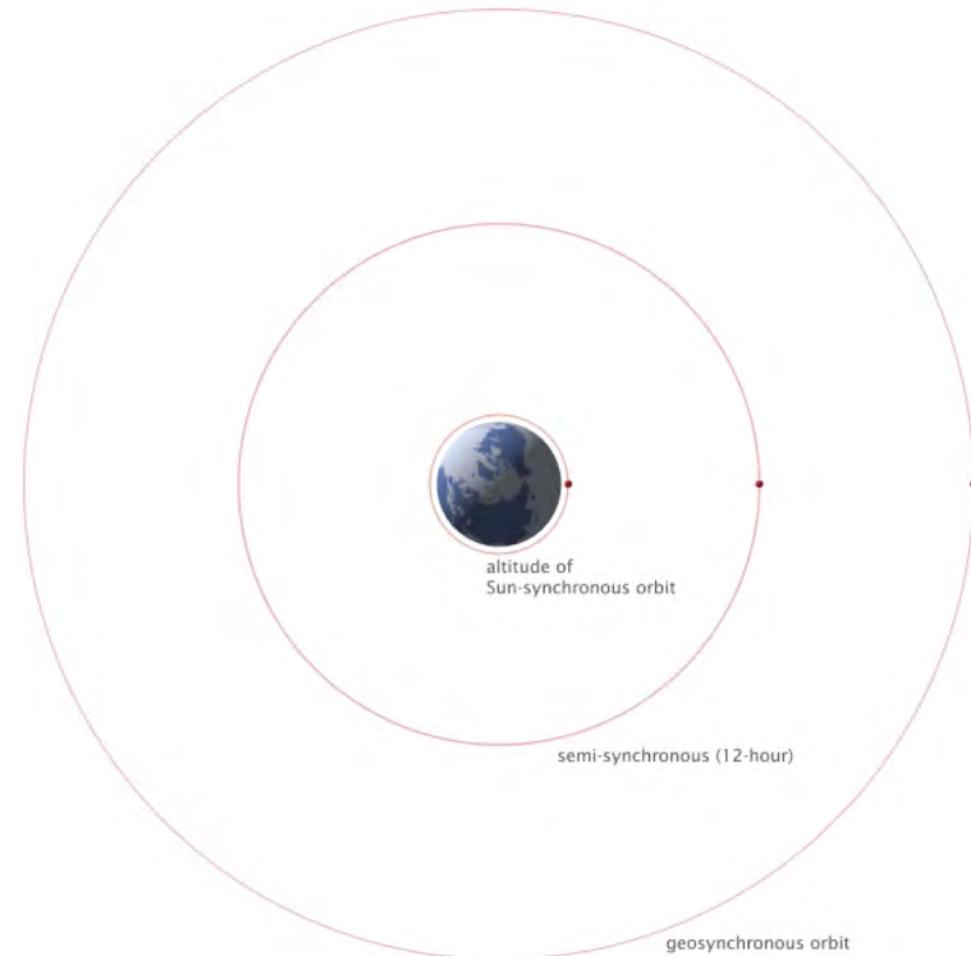


Orbiting satellite motions are controlled by Earth's gravity.

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	1440 (24 h)

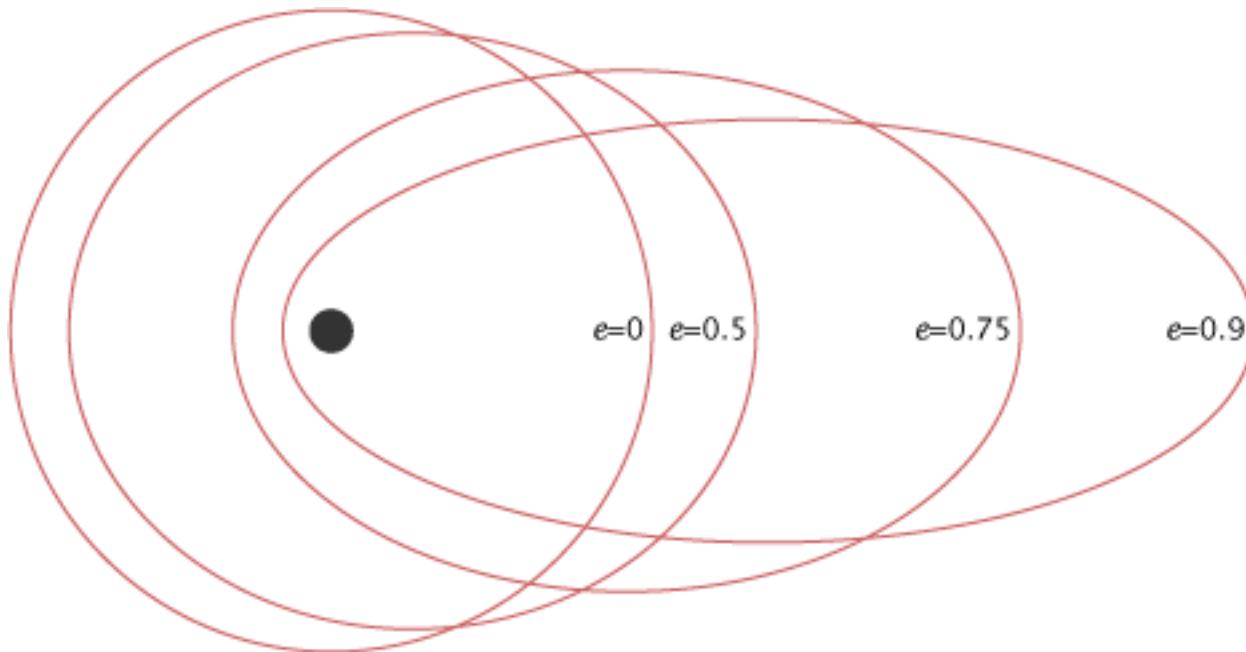
Height from the surface of Earth



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

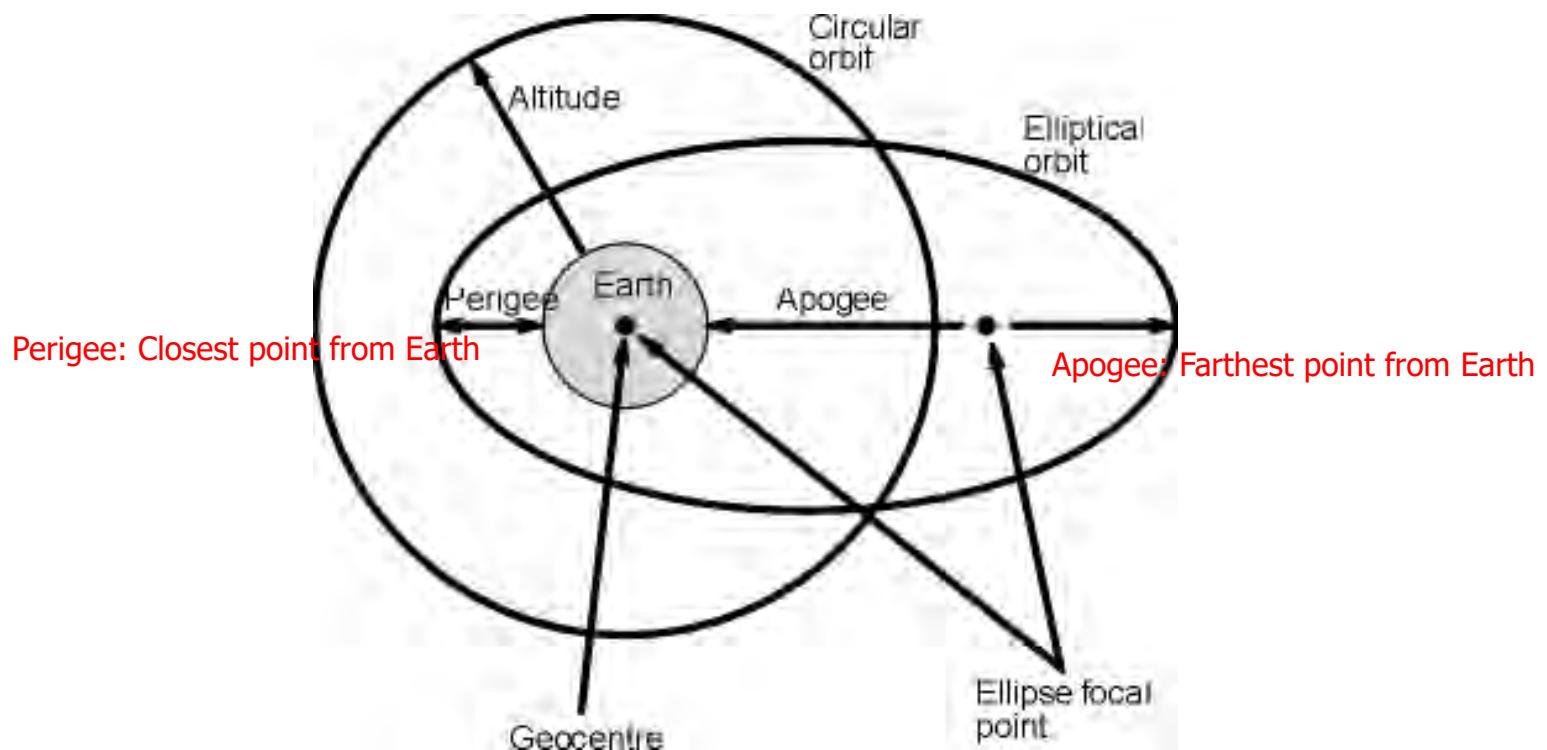


Circular orbit:

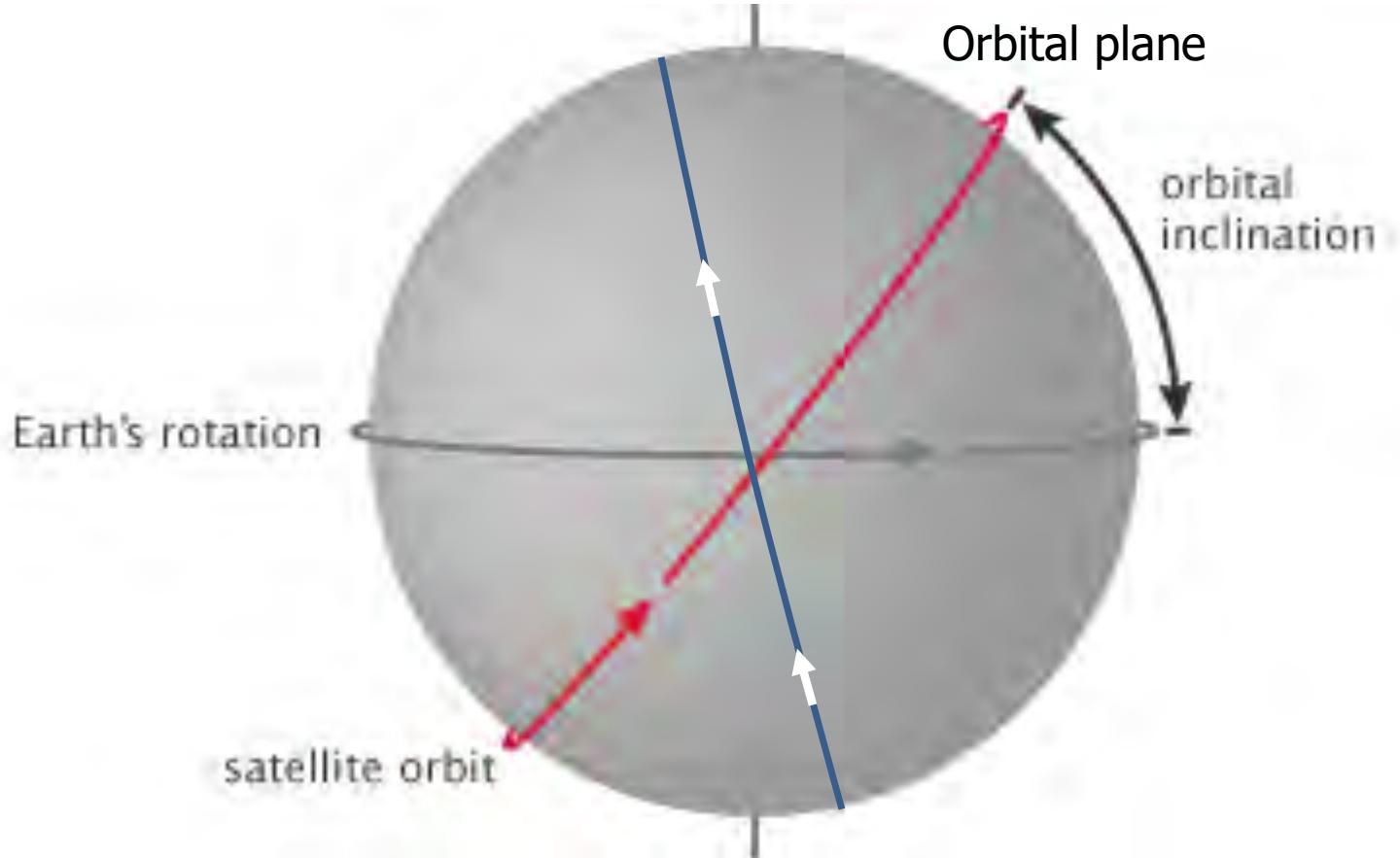
For a circular orbit, the distance from the Earth remains the same at all times.

Elliptical orbit:

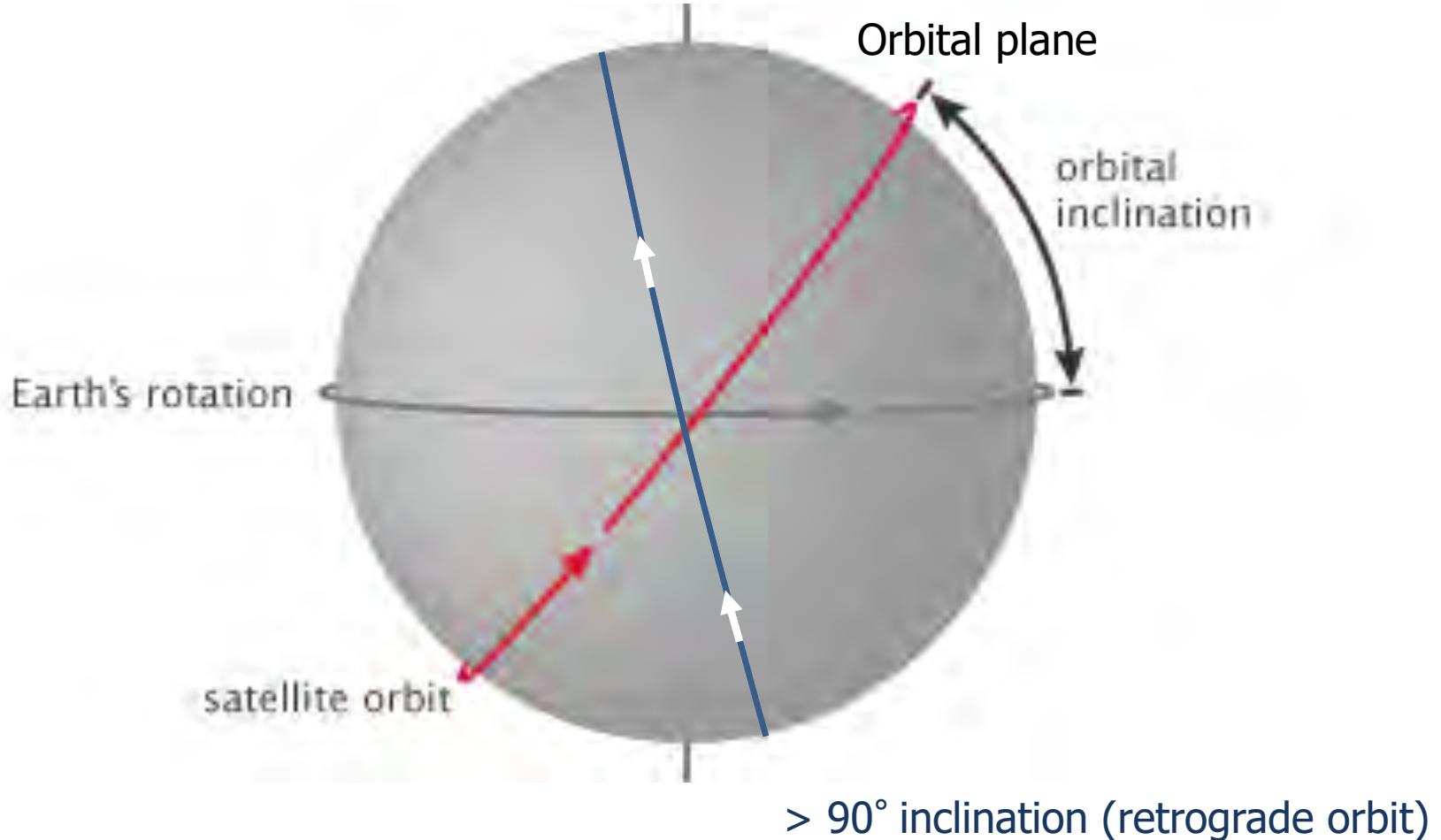
An elliptical orbit changes the distance to the Earth



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



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



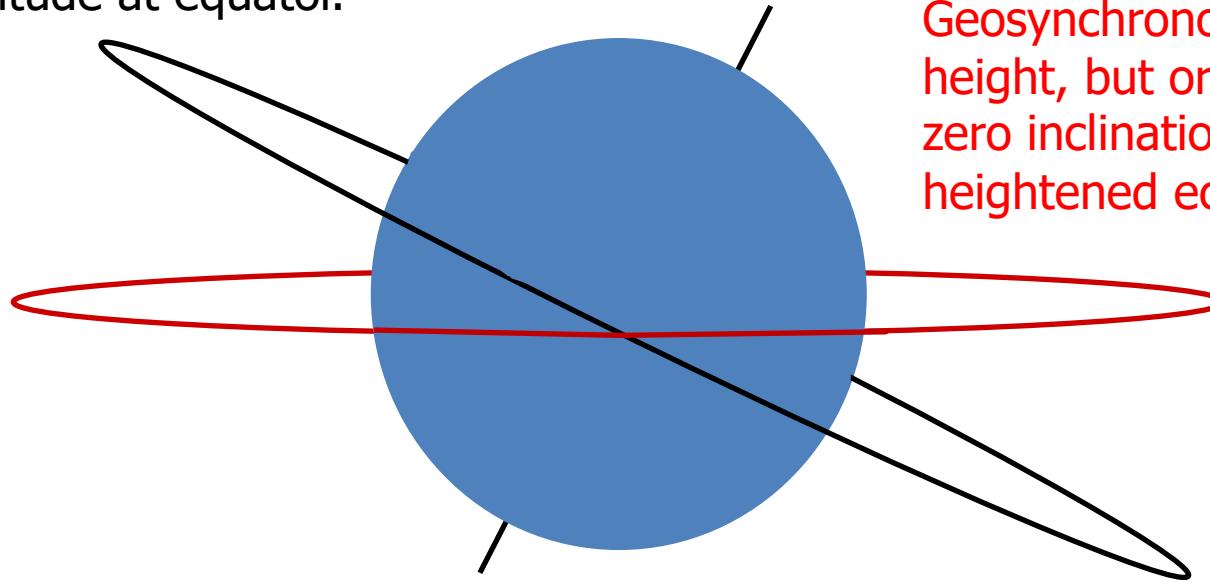
Most environmental satellite orbits are nearly circular.

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

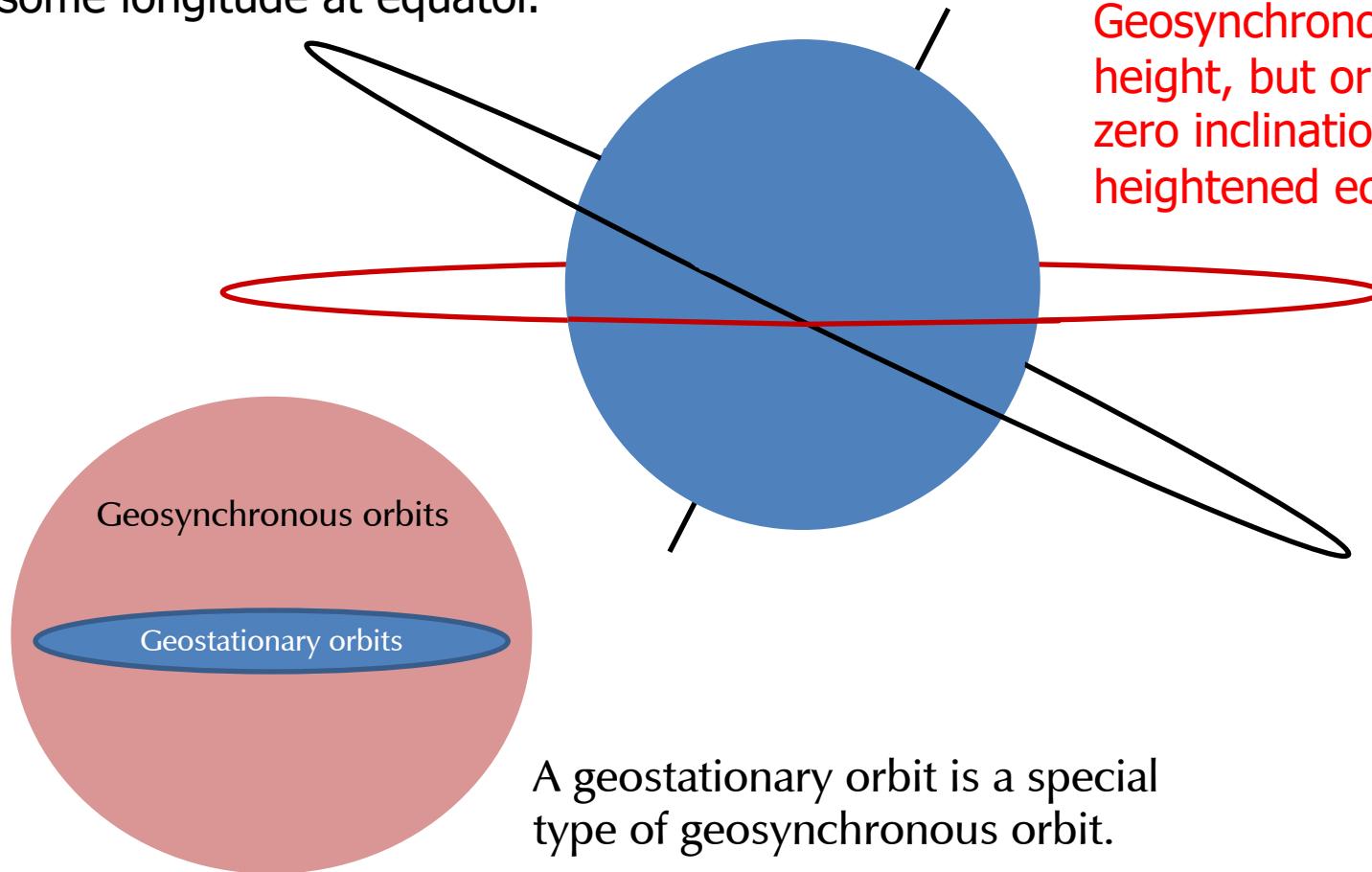
Geostationary: Fixed over some longitude at equator.



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

$$F_g = \frac{Gm_e m_s}{r^2}$$

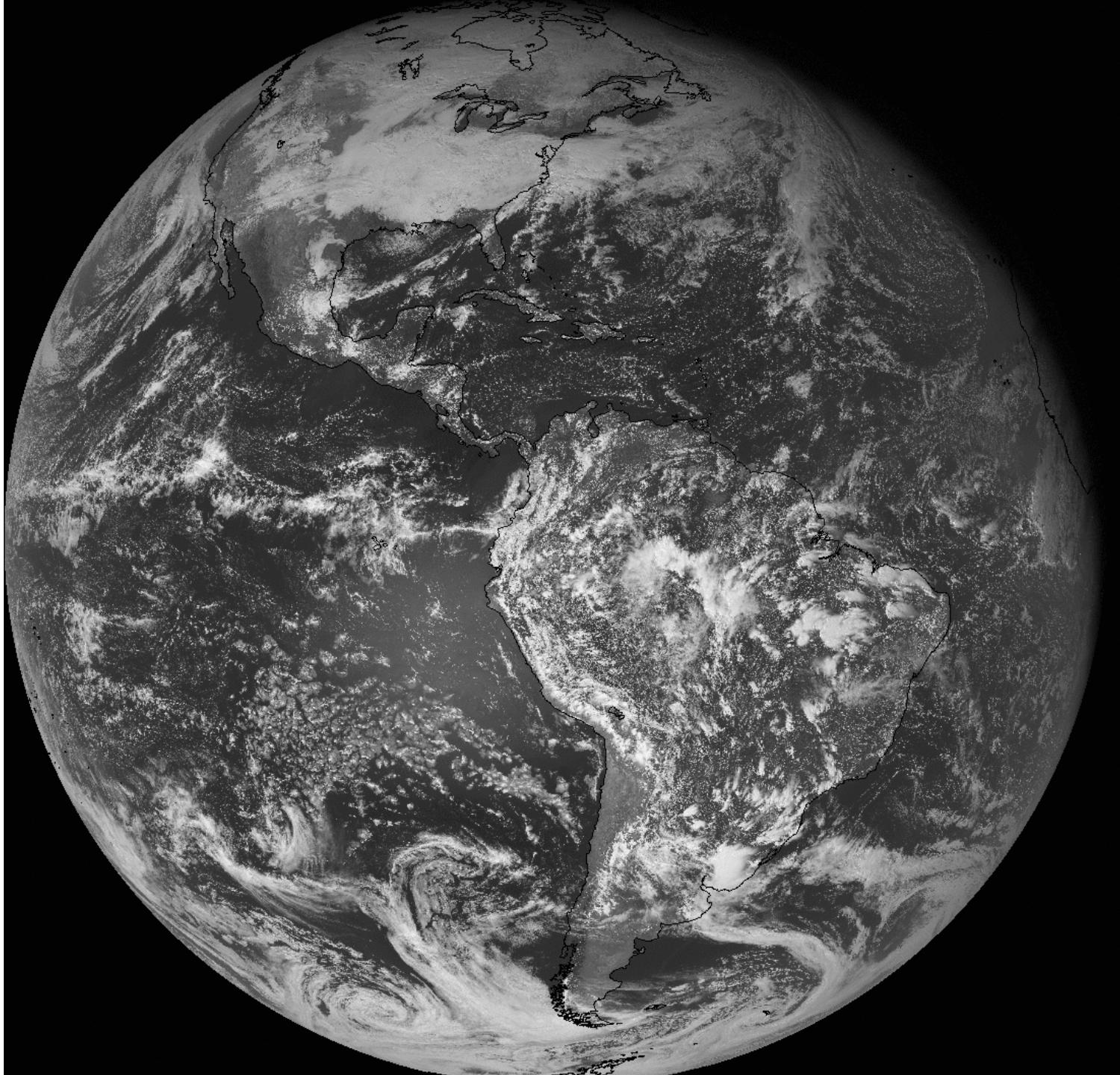
Gravitational force

$$T = \frac{2\pi r}{v}$$

$$2\pi r = \text{circular_orbit}$$

$$T^2 = \frac{4\pi^2 r^3}{Gm_e}$$

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).

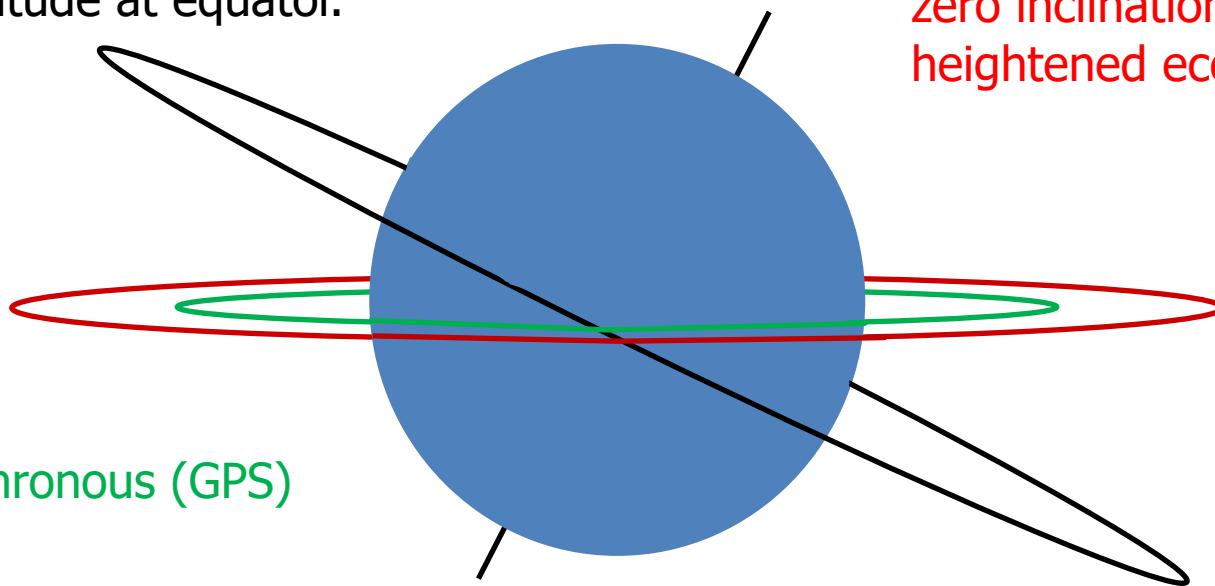
Disadvantages of geostationary orbit:

- (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.



Semi-synchronous (GPS)

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

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.

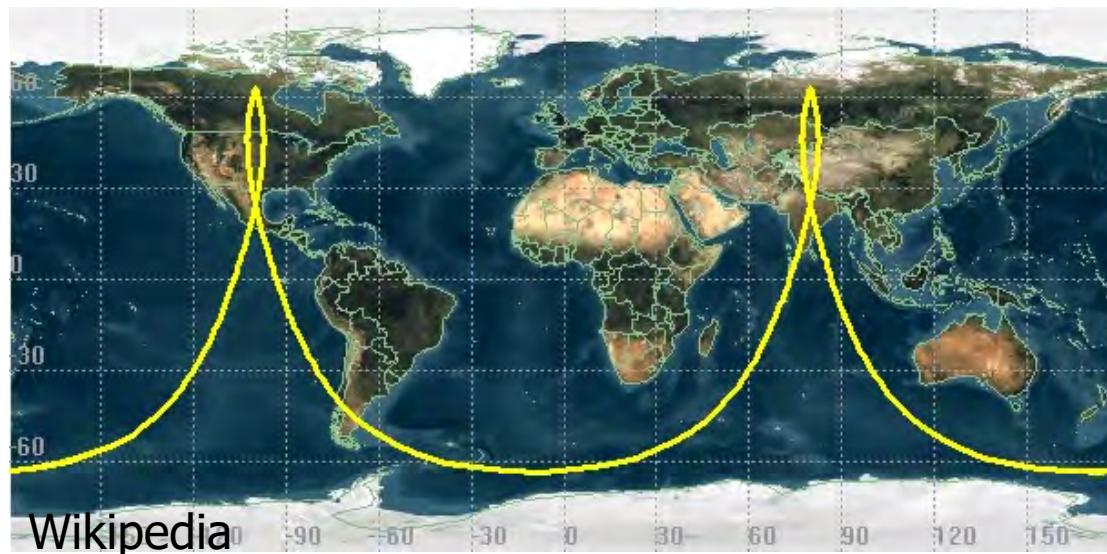
Molniya Orbit

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.

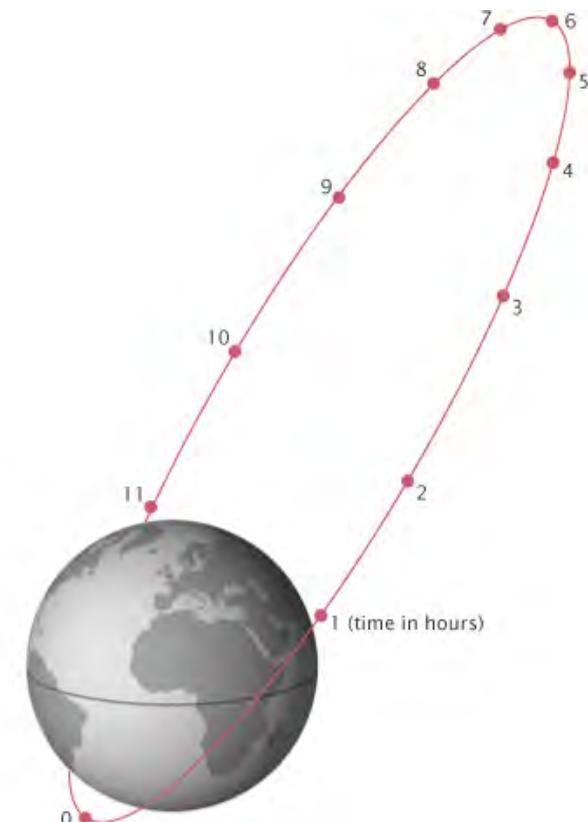
Inclination of $\sim 63.4^\circ$

Period of about $1/2$ day

Apogee is around 40,000 km



Ground track (sub-satellite point)



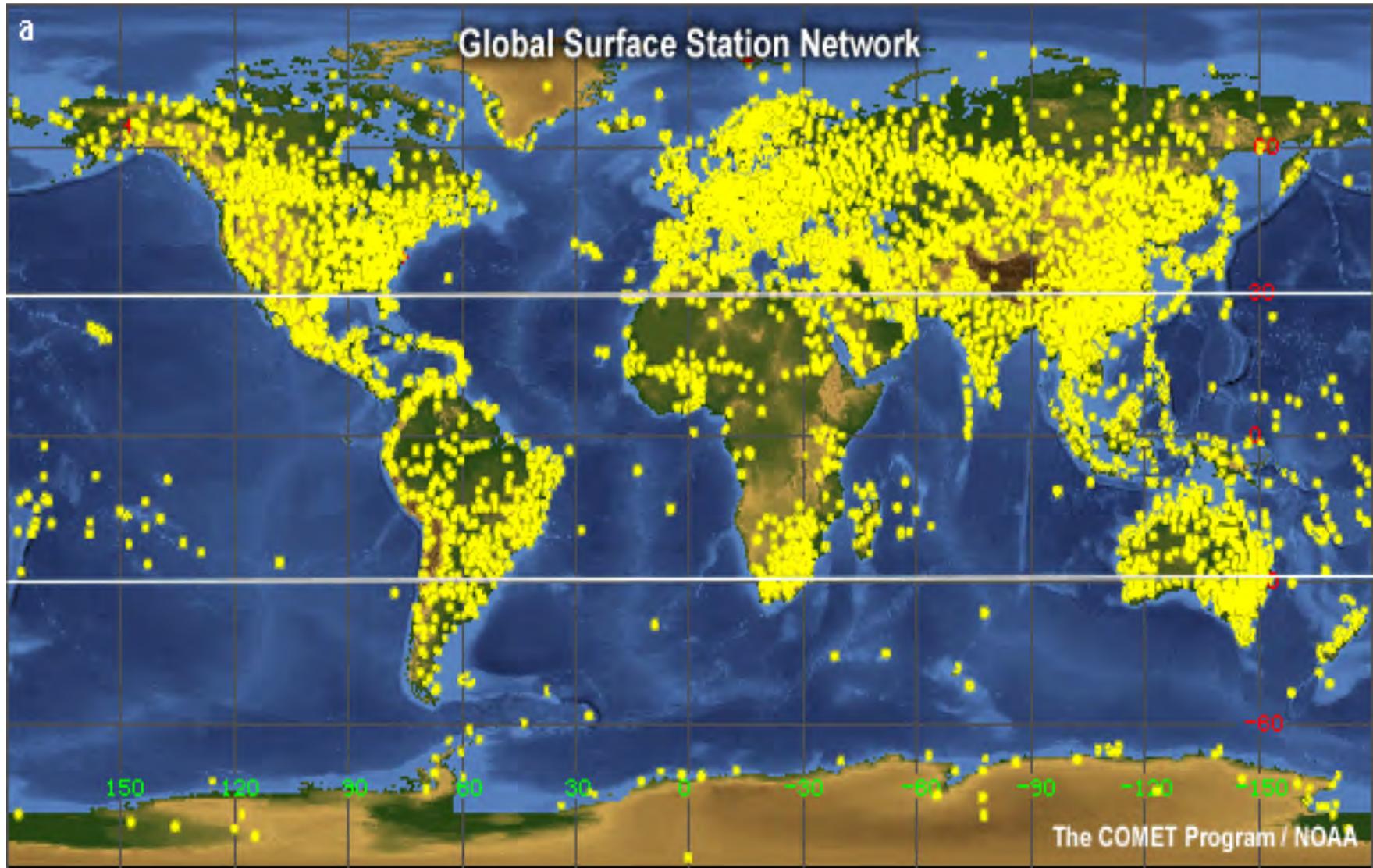
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Low-Earth orbits (LEO)

Main Topics

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

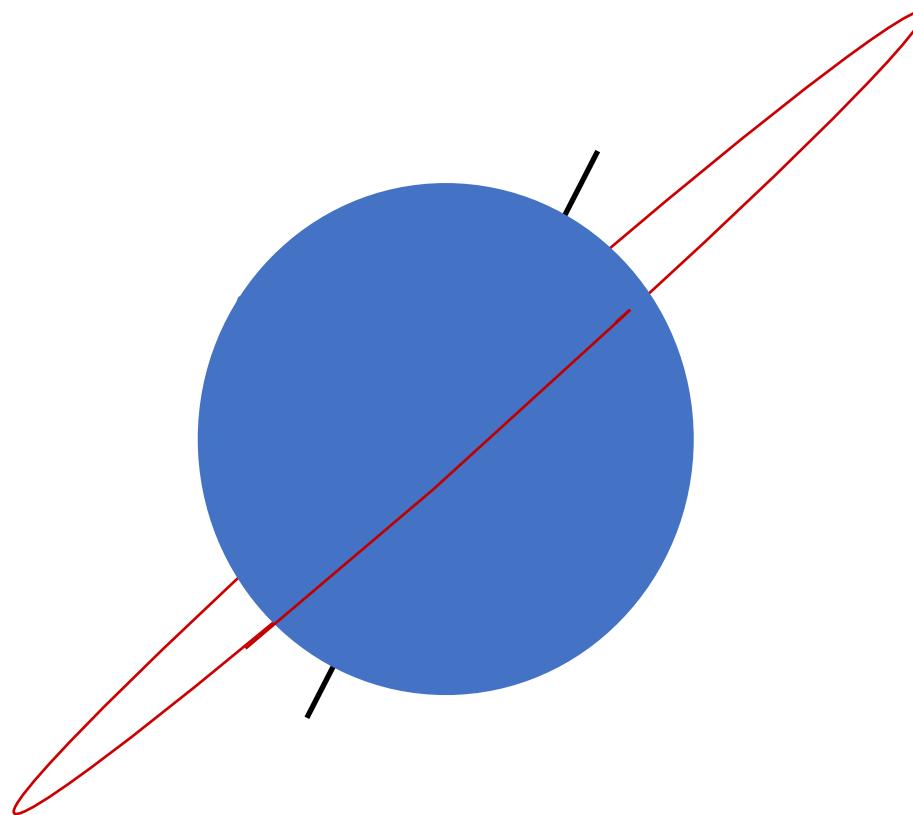
Low Earth Orbit (LEO):
Polar orbits and near-polar orbits, sun-synchronous orbits



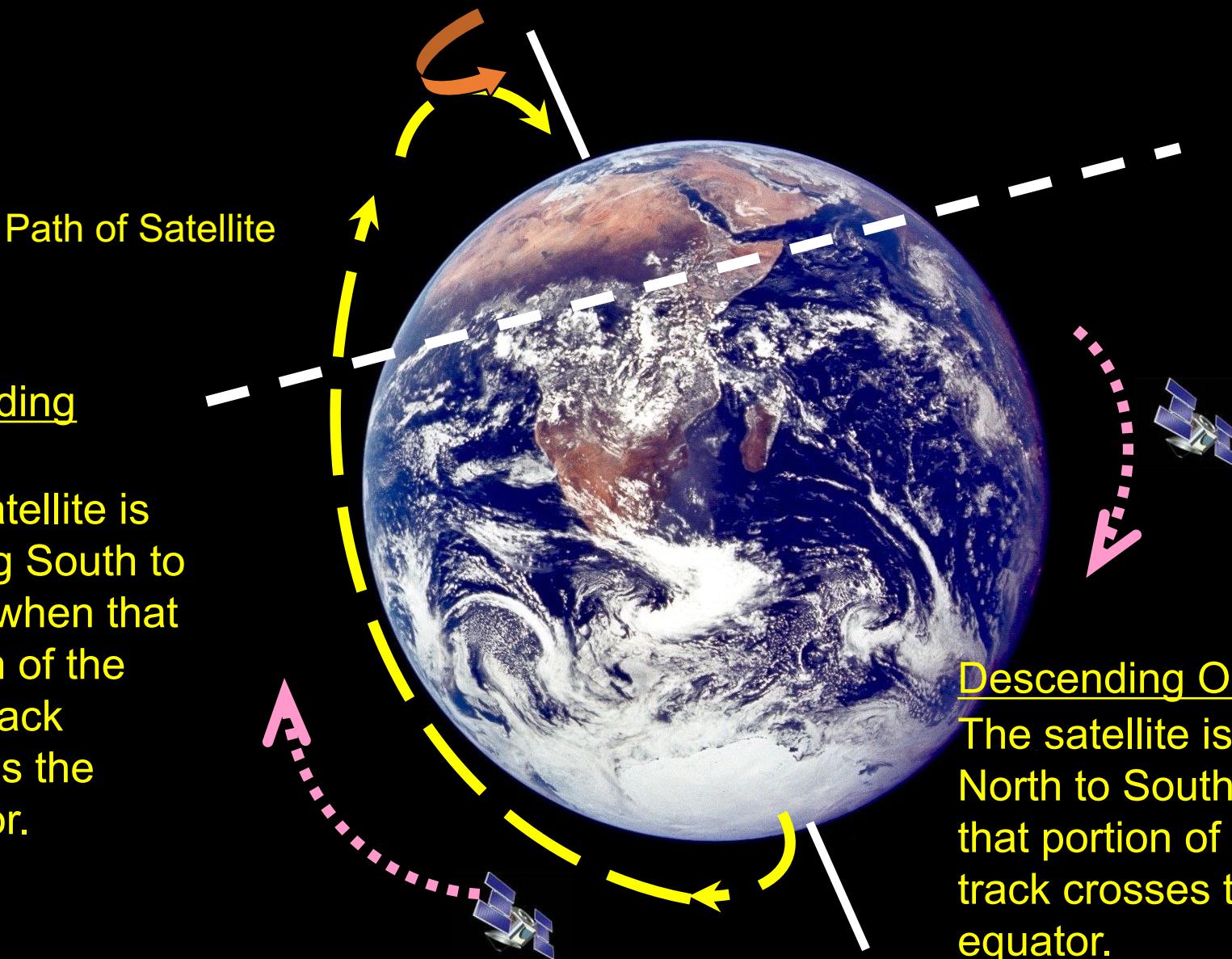
Most of Earth lacks surface and rawinsonde observations!

Low-Earth orbit satellites

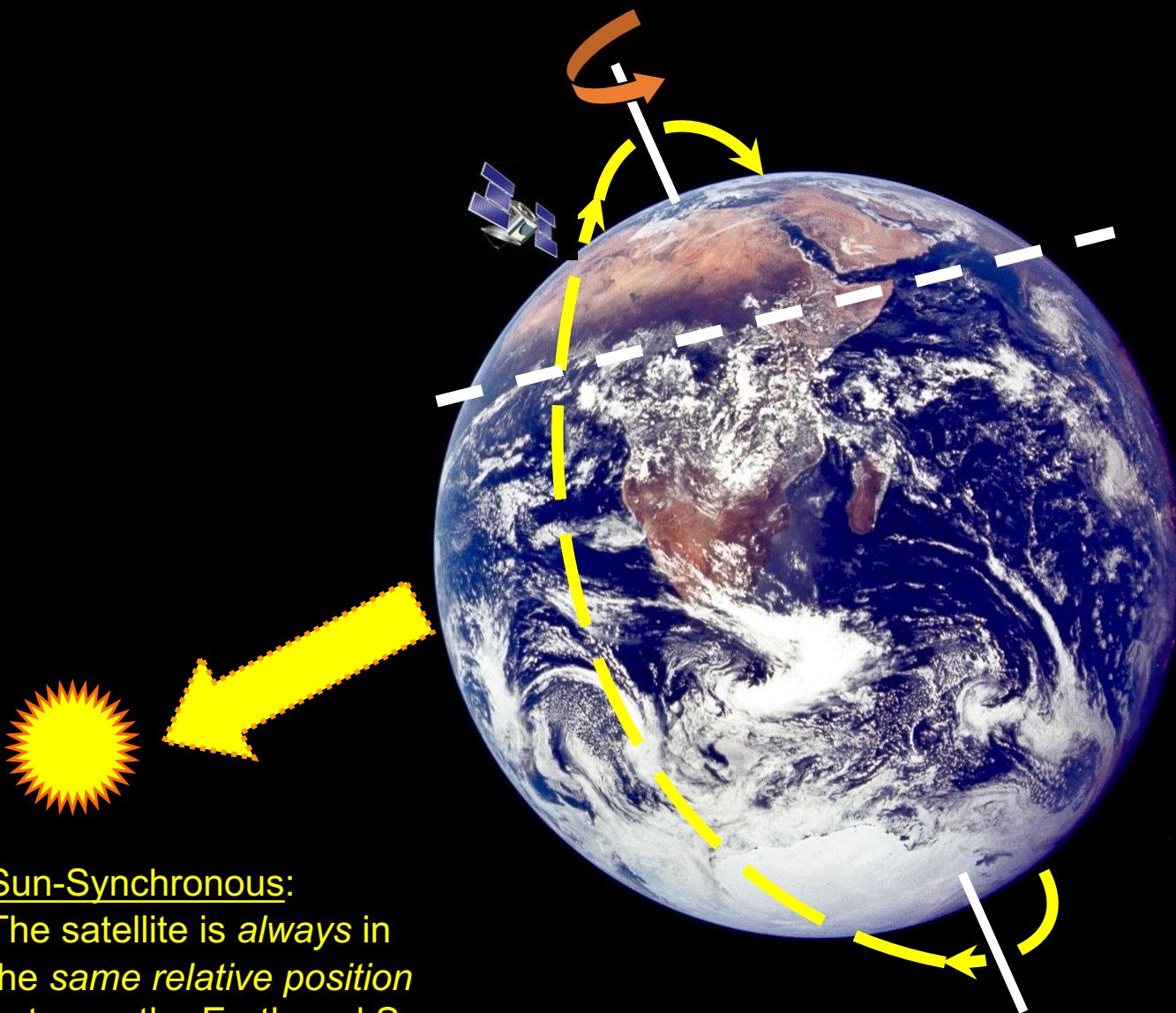
1. Circular orbit moving from pole to pole collecting data in a swath beneath them as the Earth rotates on its axis.
2. Able to collect data from large portion of Earth, including high latitudes.
1. Low orbit permits active sensing and high spatial resolution.



Low-Earth Orbits (LEO)



Low-Earth Orbits (LEO)



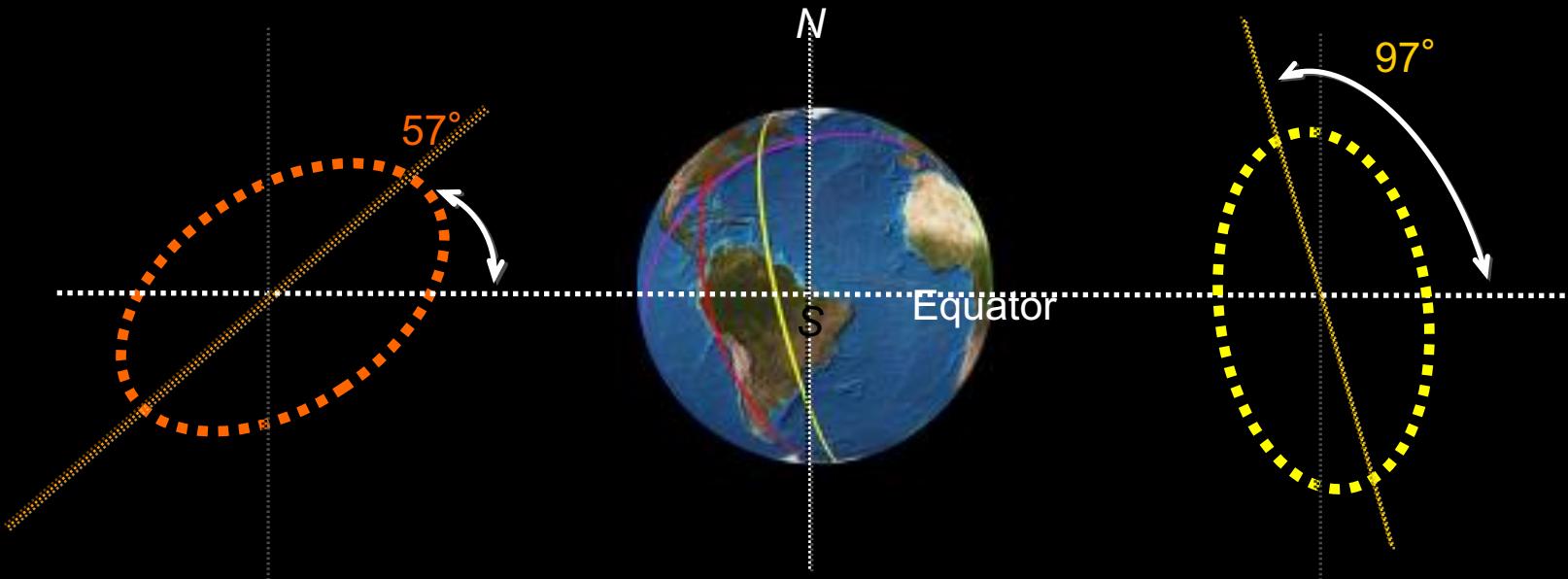
Sun-Synchronous:

The satellite is *always* in the *same relative position* between the Earth and Sun

Equator-Crossing Time:
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)

Orbital Inclination



Inclination:

The position of the orbital plane relative to the equator.

For near-polar orbits, typically about 98°.

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

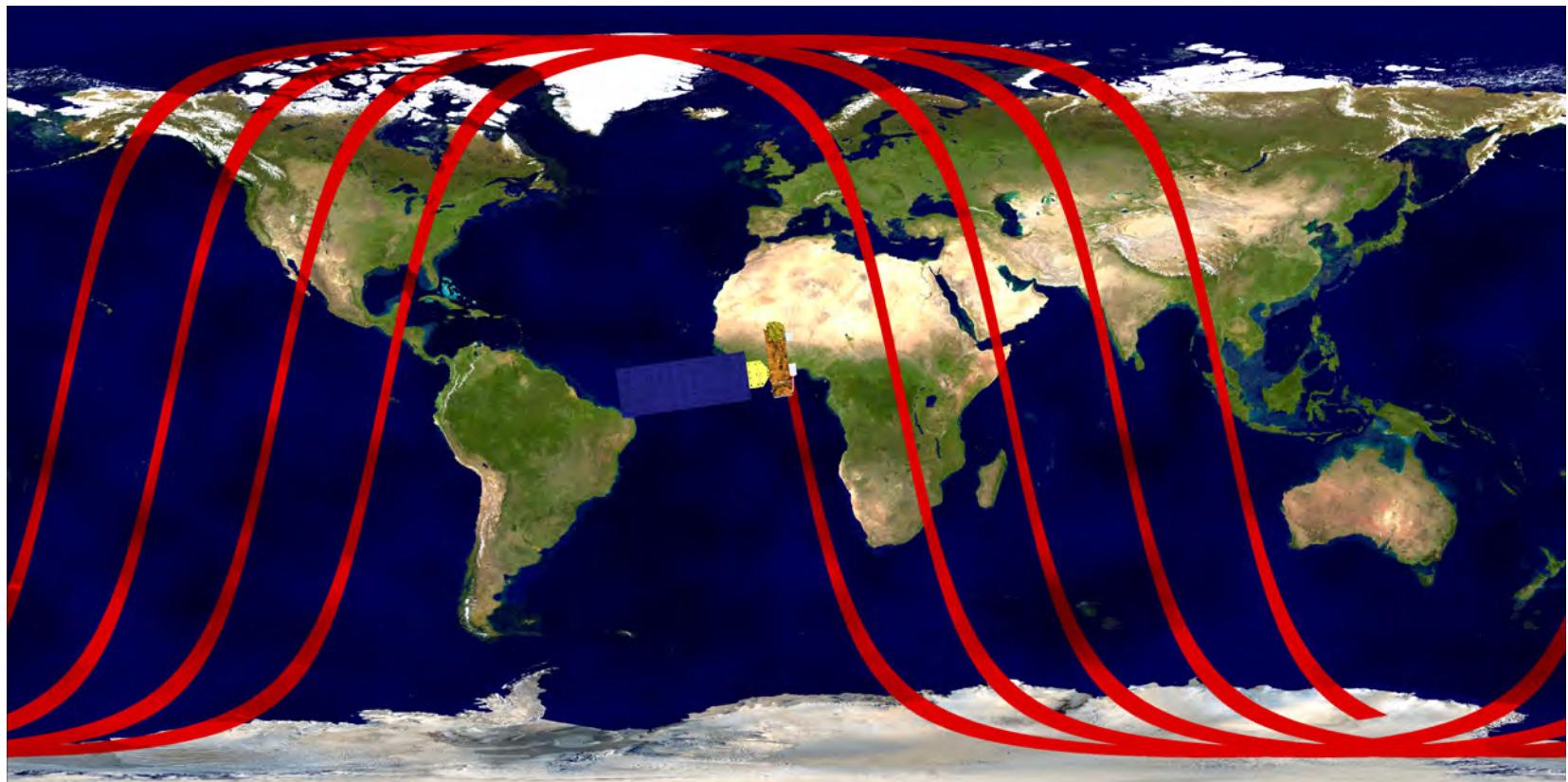
no polar coverage

High Inclination or Polar Orbit (near 90°)

virtually complete global coverage

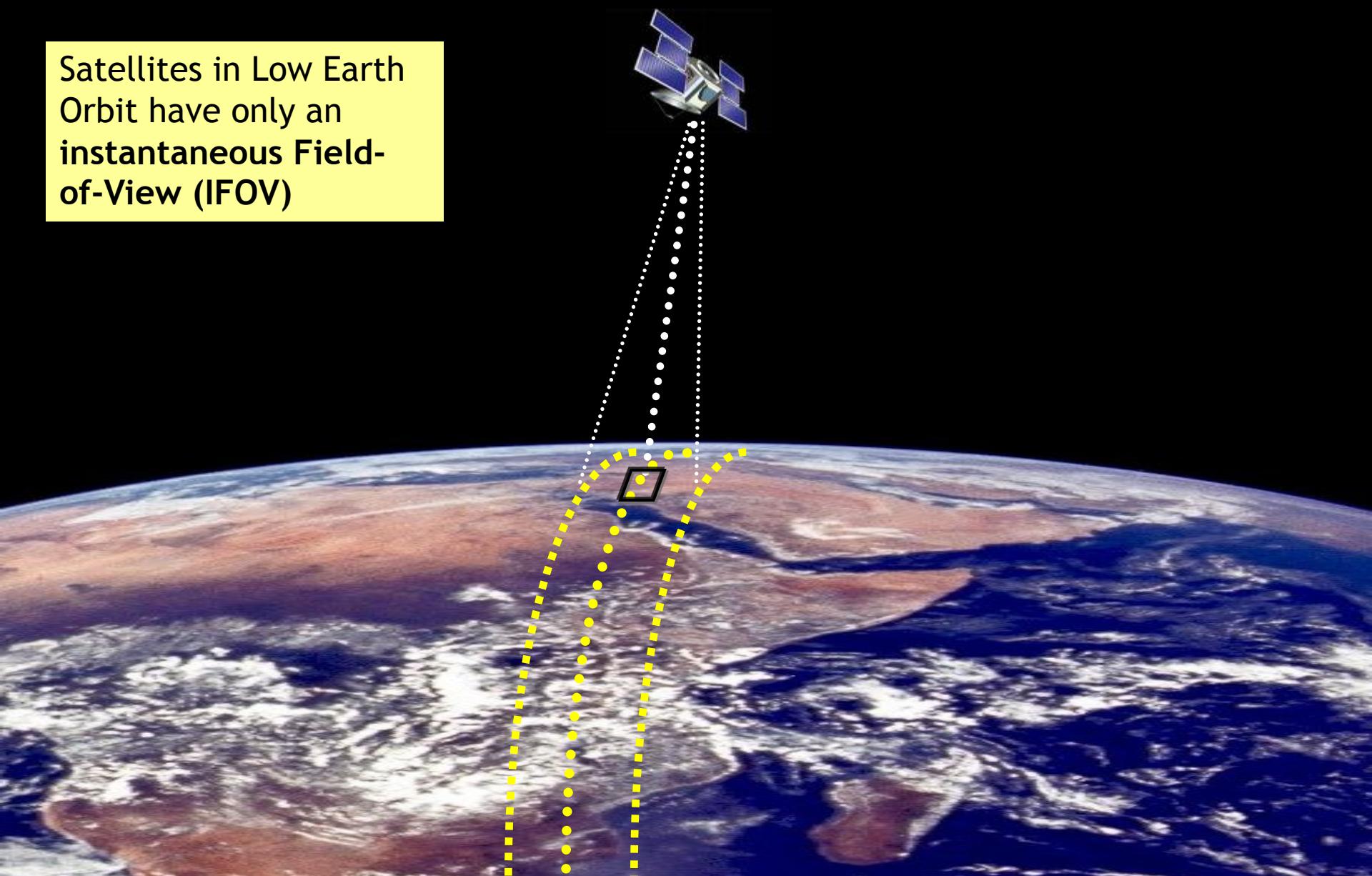
Aqua's Orbit

- 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.

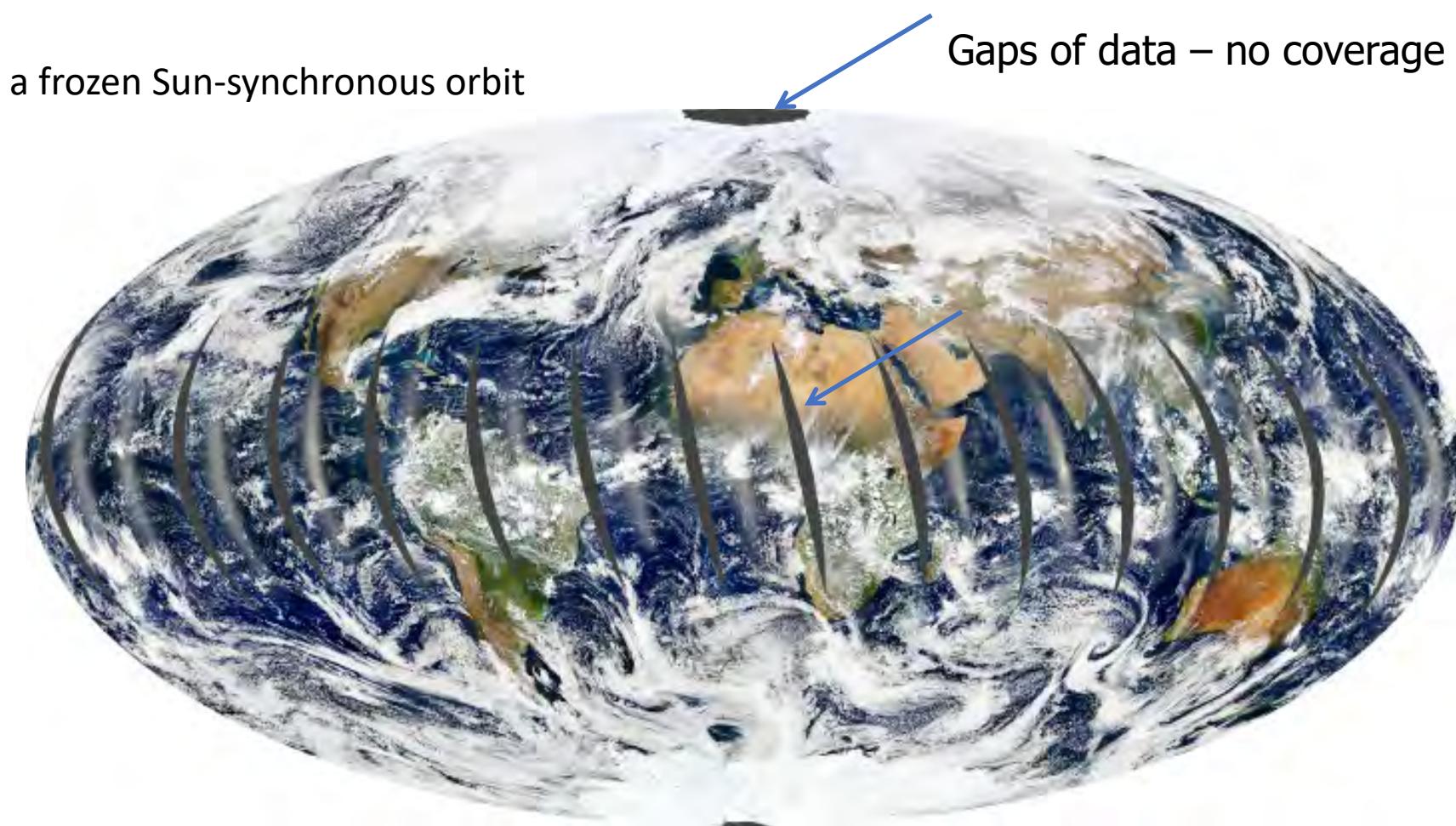


LEO Field-of-View (FOV)

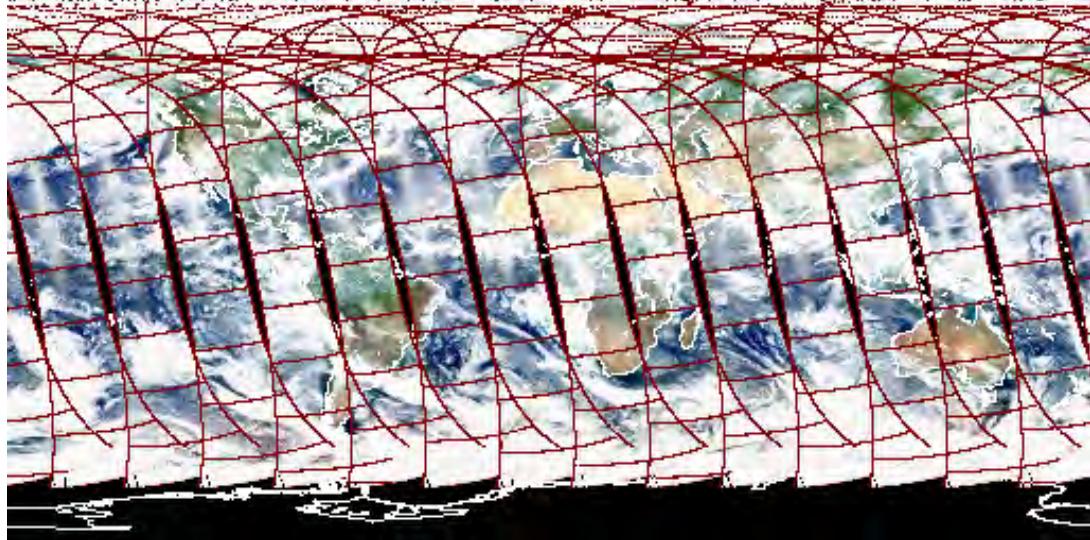
Satellites in Low Earth Orbit have only an **instantaneous Field-of-View (IFOV)**



Consistency of measurements -> they need to be taken at about the same time of day to ensure that the angle of sunlight incident on atmosphere and/or Earth's surface is as consistent as possible.

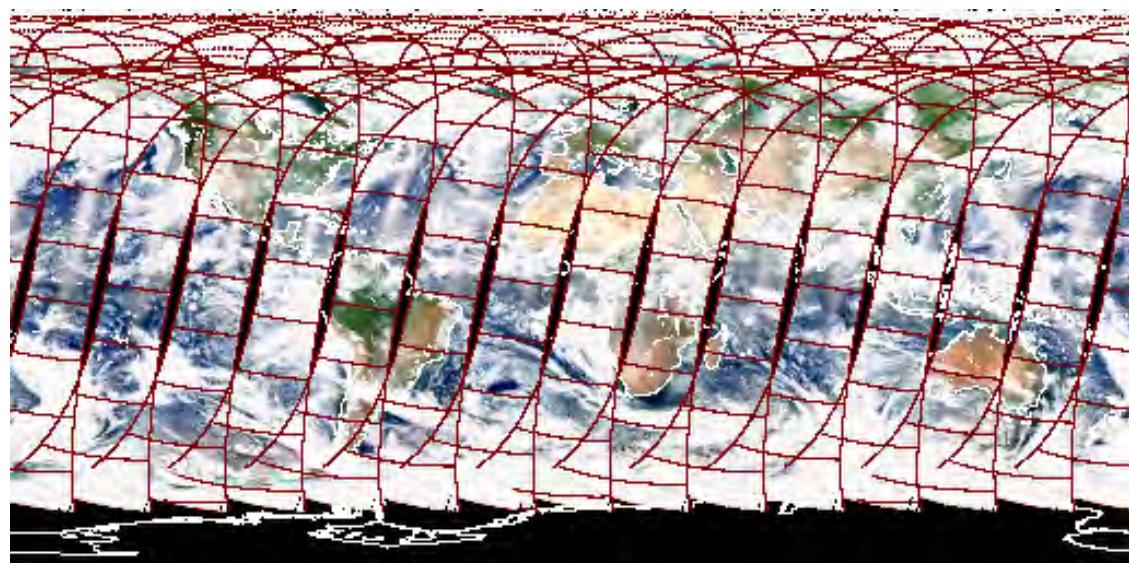


Aqua (“ascending” orbit) day time

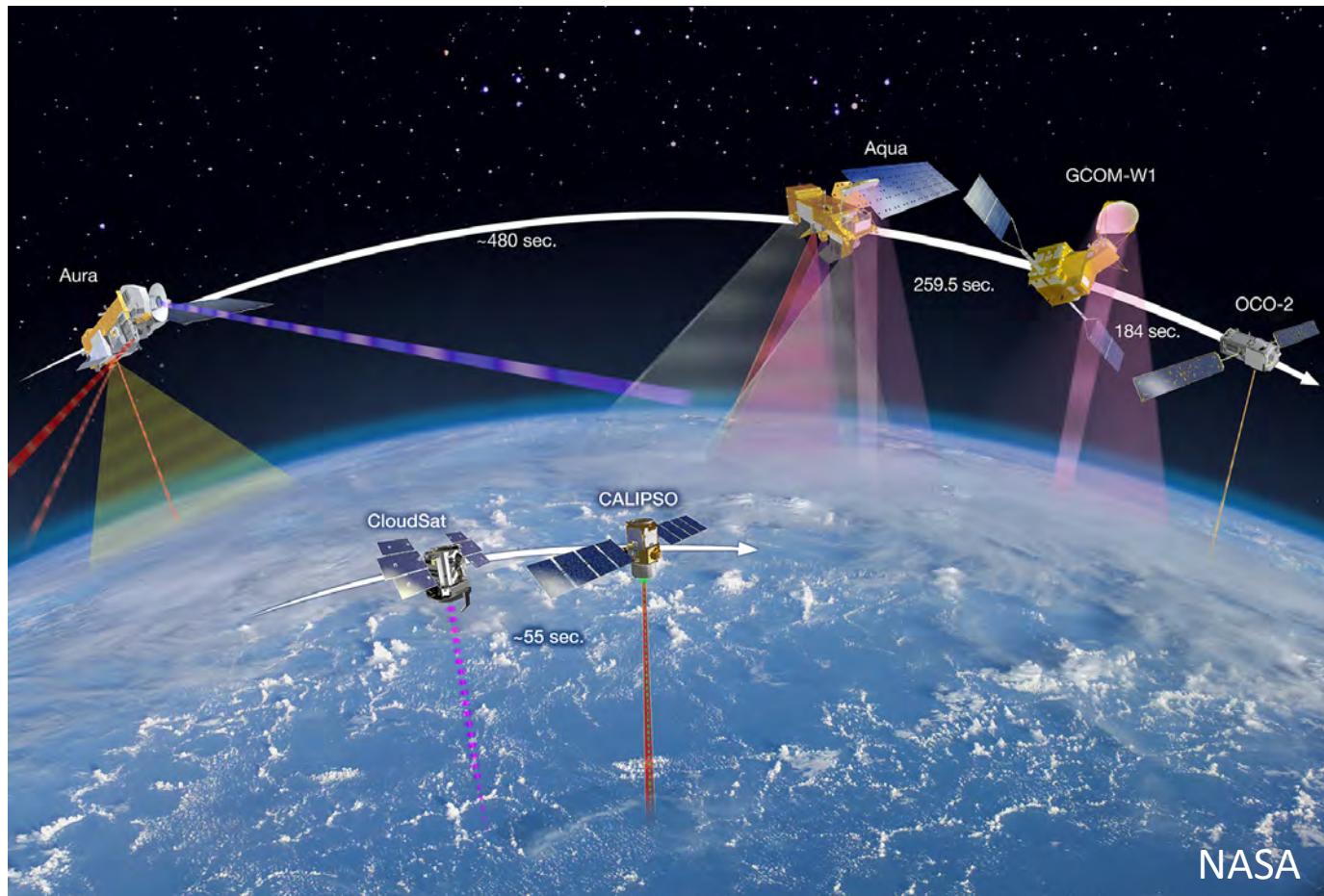


LEO Sun-synchronous
Orbiting

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*	Temperature and composition of the upper troposphere, stratosphere, and mesosphere; aerosol extinction and cloud height *Inoperative since 2008
	MLS	Temperature and composition of the upper troposphere and stratosphere; upper tropospheric cloud ice
	OMI	Total column ozone, nitrogen dioxide, sulfur dioxide, formaldehyde, bromine monoxide, aerosol absorption, and cloud centroid pressure
	TES*	Temperature, ozone, carbon monoxide, and water vapor profiles from the surface to lower stratosphere
PARASOL*	POLDER	Polarized light measurements of clouds and aerosols *Inoperative since 2013
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	Nadir-viewing, non-scanning imager
	WFC	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	Highly accurate temperature profiles within the atmosphere
	AMSR-E*	Precipitation rate, cloud water, water vapor, sea-surface winds, sea-surface temperatures, ice, snow, and soil moisture *Inoperative since 2015
	AMSU-A	Temperature profiles in the upper atmosphere, especially in the stratosphere
	CERES	Solar-reflected and Earth-emitted radiation; cloud properties (altitude, thickness, and size of the cloud particles)
	HSB*	Humidity Sounder for Brazil *Inoperative since 2003
	MODIS	Vegetation, land surface cover, ocean chlorophyll fluorescence, cloud and aerosol properties, fire occurrence, land snow cover, and sea ice cover
	AMSR2	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>