



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

Lecture 18: Satellite Orbits

The Importance of Satellite Orbits

How does the choice of orbit affect the remote sensing mission?

- View of satellite?
- Revisit time of satellite to a point on earth?
- Thermal control on the satellite?
- Space radiation and gravitational environment?
- Amount of data that can be transferred between the satellite and ground?
- Power generation for the satellite?
- Launch costs?

Outline

- **Circular Orbits**

- **Keplerian (elliptical) Orbits**

- **Meteorological satellite orbits:**

- 1) geostationary**

- 2) sun-synchronous**

- 3) other orbits**

Newton's Law of Universal Gravitation

- The force of attraction between two point mass m_1 and m_2 separated by a distance r is

$$F = \frac{Gm_1m_2}{r^2}$$

- Where G is the universal gravitation constant

Circular Satellite Orbit

- Assuming that the earth is a sphere, we can treat it as a point mass.

$$\frac{mv^2}{r} = \frac{Gm_e m}{r^2}$$

- Where v is the orbital velocity of the satellite. M is the mass of satellite, and m_e is the mass of earth. mv^2/r is the centripital force required to keep the satellite in a circular orbit.
- The orbit of a satellite is independent of its mass.

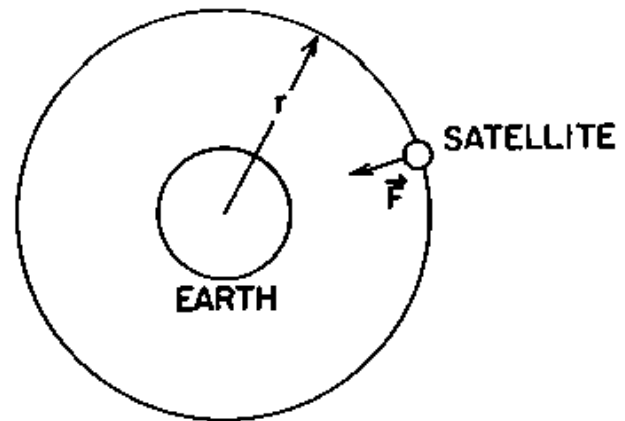


FIGURE 2.1. A circular satellite orbit.

Calculating the height of a Satellite in Geostationary Orbit

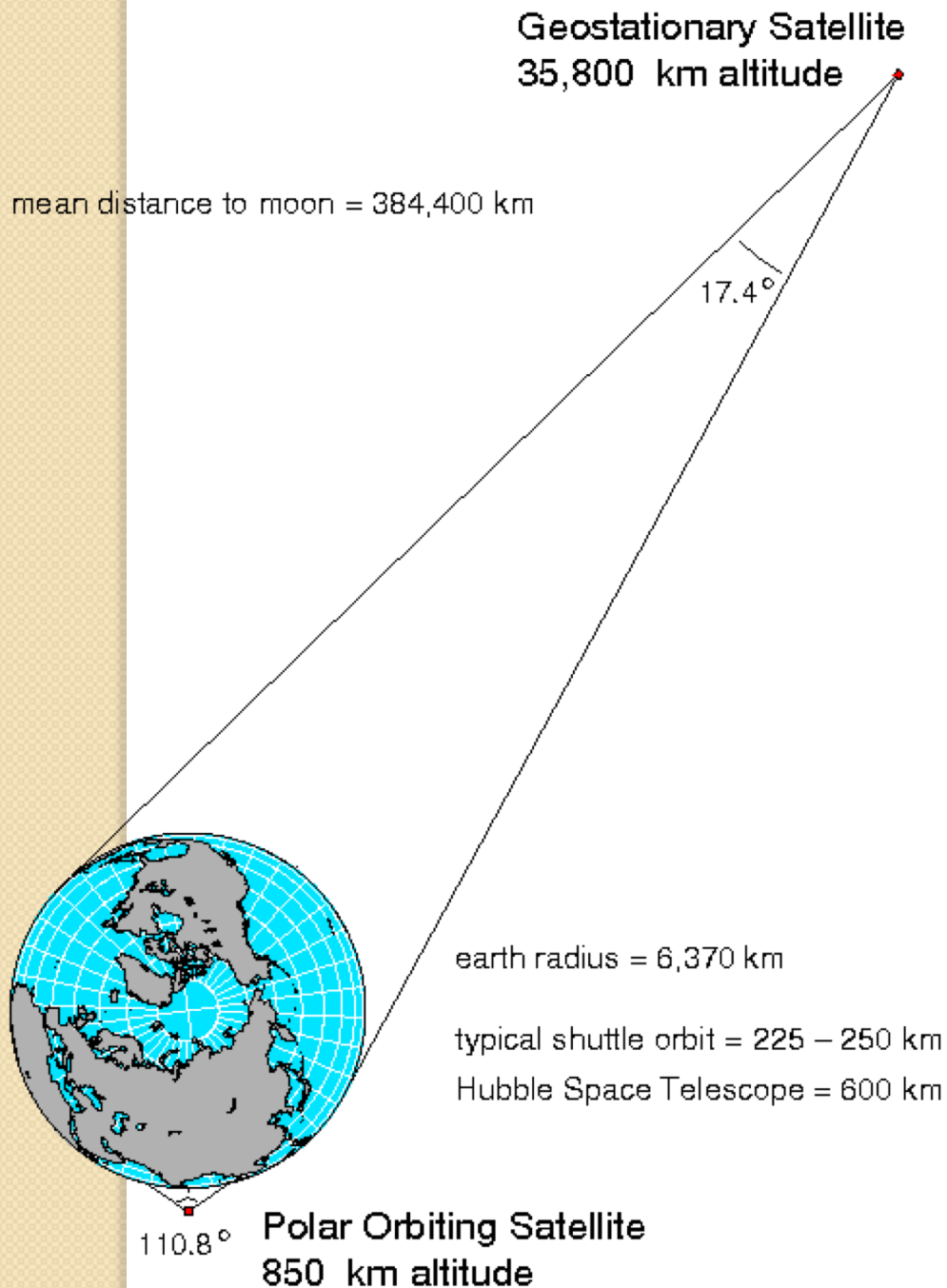
- The satellite in geostationary orbit has the same angular velocity as the earth. The angular velocity of a satellite is,

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

- Where T is the period of the satellite. Therefore,

$$r^3 = \frac{Gm_e}{\xi^2}$$

- Inserting the angular velocity of the Earth, we get: $r=42,164$ km, which means that the altitude of a satellite in geostationary orbit is **35,786 km** above the Earth's surface.



- For the polar orbiting satellite with 850 km altitude, we can get its period T of about 102 min.

- However, satellite do not travel in perfect circles. Therefore we need to derive the exact form of a satellite orbit using ellipse geometry.

Ellipse Geometry

- Perigee: the point where the satellite is closest to the Earth.
- Apogee: : the point where the satellite is furthest from the Earth.
- a =Semimajor axis;
- d =the distance from the center of the ellipse to one focus
- Eccentricity: $\varepsilon=d/a$ ($0\leq\varepsilon<1$)
- Θ is the true anomaly and is always measured counterclockwise from the perigee.
- The equation for the path that the satellite follows:

$$r = \frac{a(1 - \varepsilon^2)}{1 + \varepsilon \cos \theta}$$

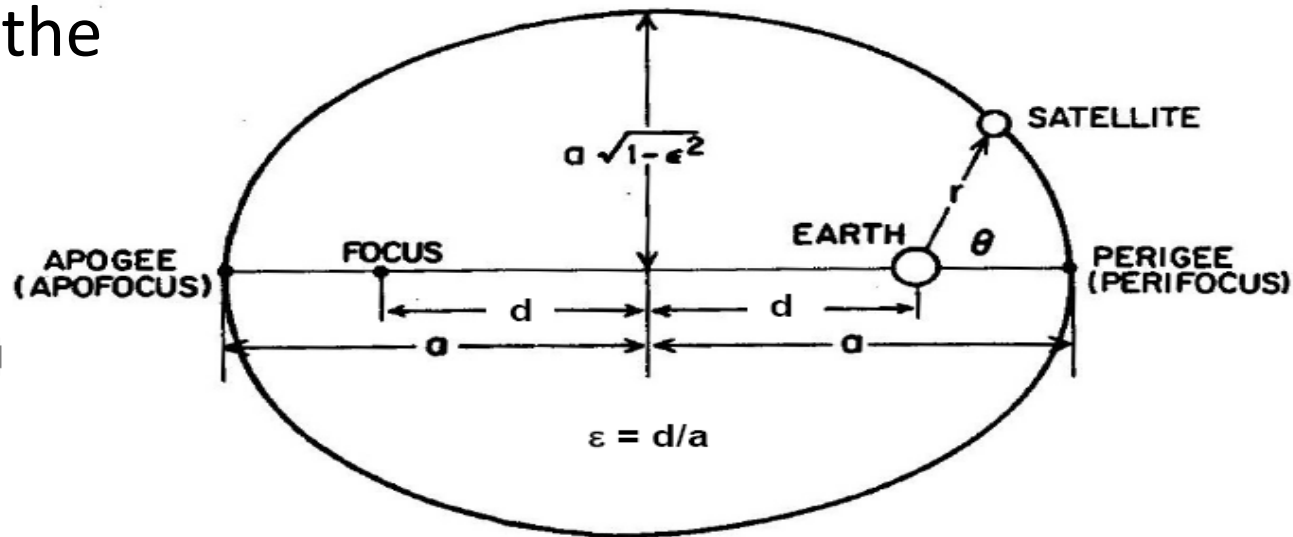


FIGURE 2.2. Elliptical orbit geometry.

Kepler's Laws

1. All satellites travel in ellipse paths with the Earth at one focus.
 2. The radius vector from the Earth to a satellite sweeps out equal areas in equal times.
- A satellite in a circular orbit undergoes uniform angular velocity. Its path can be derived from Newton's laws.
 - A satellite in an elliptical orbit cannot have uniform angular velocity; **it must travel faster** when it is closer to Earth. Its path can be derived from Kepler's equation.

Satellite Position

- By calculating radius r and true anomaly Θ at time t , we can position the satellite in the plane of its orbit using Kepler's Equation.

Then what about the orbital plane position in space?

- We need to define a 3D coordinate system first.
- This system must be an inertial coordinate system (non-accelerating), not the one fixed to the rotating Earth as we had before.
- We will adopt an astronomical coordinate system.

The right-ascension-declination coordinate System

- Z axis: Earth's spin axis
- X axis: points from the Earth's center to the sun at the moment of the vernal (spring) equinox, when the sun is crossing the equatorial plane from the Southern hemisphere to the Northern hemisphere.
- Y axis: is chosen to make it a right-handed coordinate system.

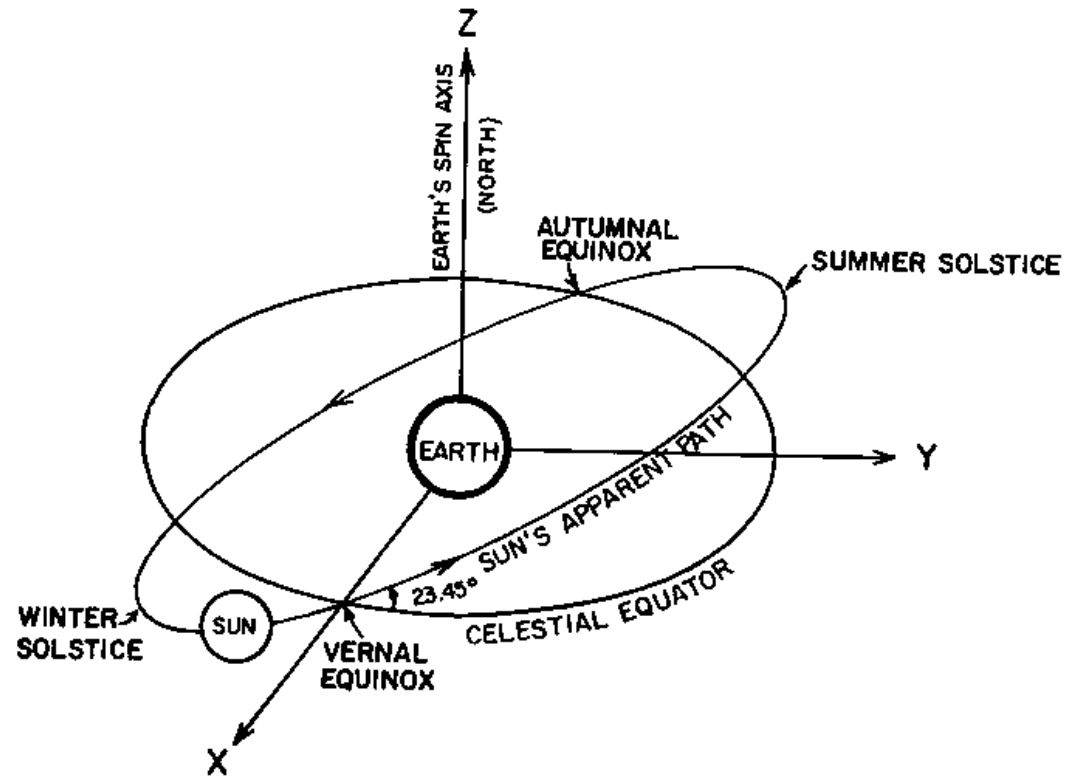


FIGURE 2.4. The right ascension–declination coordinate system.

Coordinates used in the right-ascension-declination coordinate System

- **Right ascension Ω** : is the angular displacement, measured counterclockwise from x-axis, of the projection of the point in the equatorial plane.
- **Declination (δ)** of a satellite in space is its angular displacement measured northward from the equatorial plane.
- **Radius (r)** is the distance between Earth and the satellite.

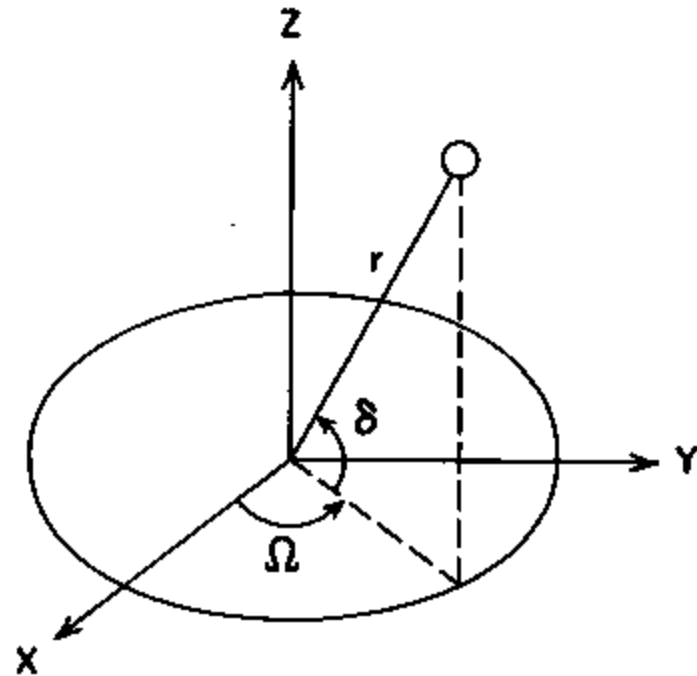


Fig. 2.5 Coordinates used in the right-ascension-declination coordinate system: right ascension (Ω), declination (δ), and radius (r).

Three Angles to Position an Elliptical Orbit in Space

- These three angles are:
 - Inclination angle i ,
 - Right ascension of ascending node Ω ,
 - Argument of perigee ω .

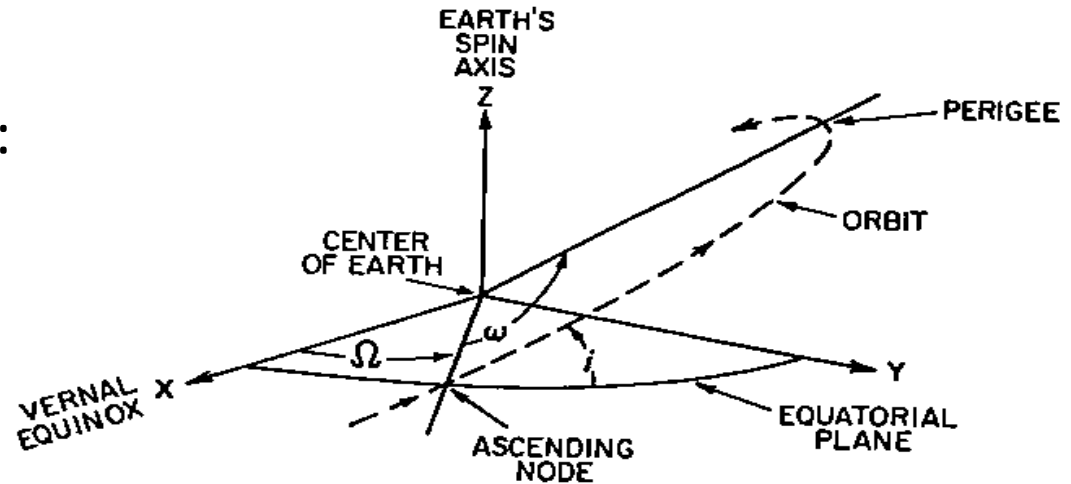


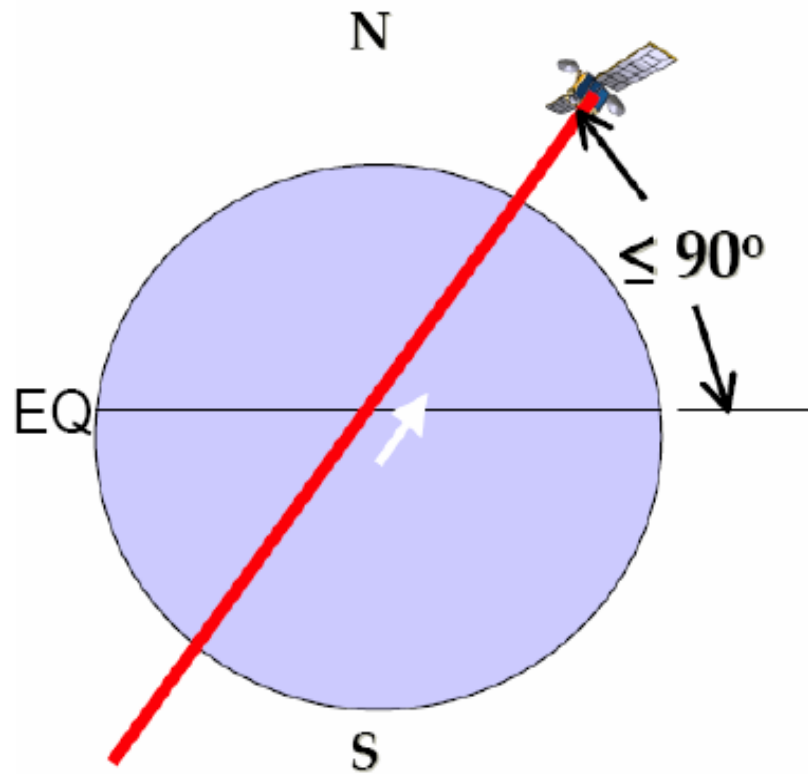
FIGURE 2.6. Angles used to orient an orbit in space.

- **Inclination angle i :** is the angle between the equatorial plane and the orbital plane.
- **Ascending node** is the point where the satellite crosses the equatorial plane going north (ascends). The right ascension of this point Ω is the second angle. It is also the right ascension of the intersection of the orbital plane with the equatorial plane. Thus it is always defined, not just when the satellite is at an ascending node.
- **Argument of perigee (ω):** is the angle measured in the orbital plane between the ascending node and the perigee.

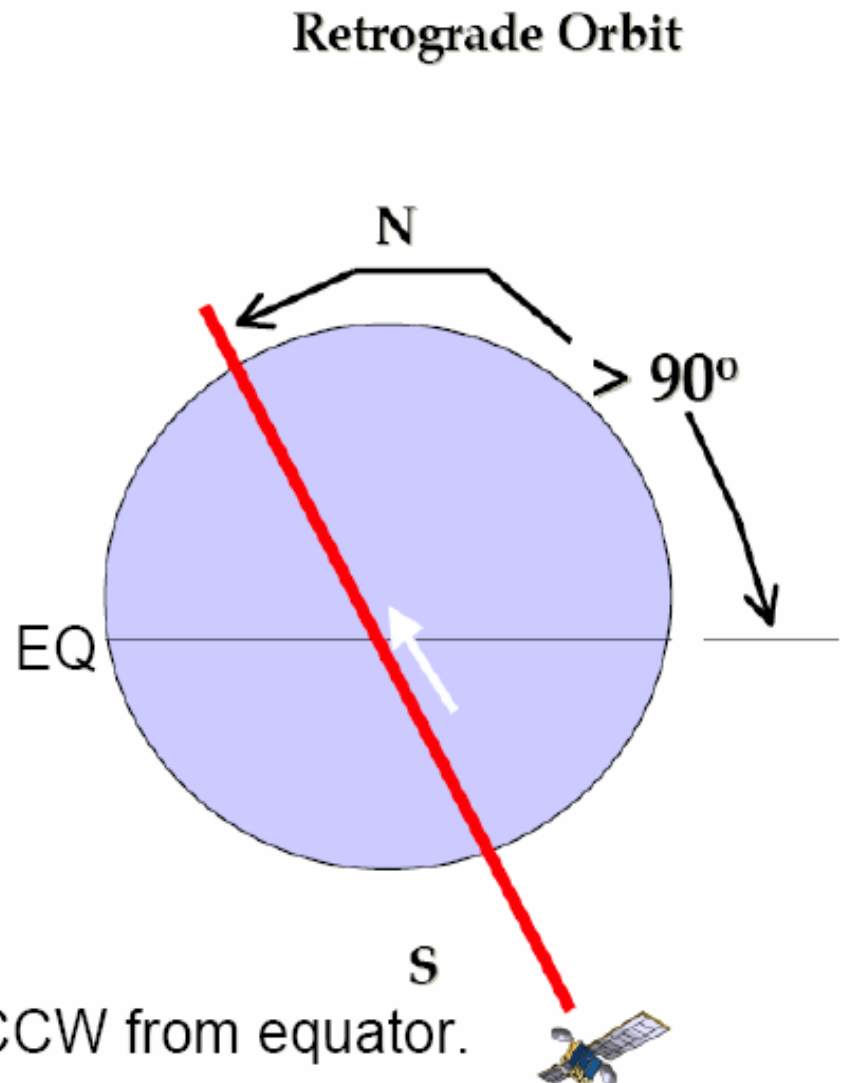
Inclination Angle

- **Inclination angle i :** is the angle between the equatorial plane and the orbital plane.
- By convention, the inclination angle is **zero** if the orbital plane coincides with the equatorial plane and if the satellite rotates in the same direction as the Earth. If the two planes coincide but the satellite rotates opposite to as the Earth, the inclination angle is **180 degree**.
- **Prograde** orbits are those with inclination angle less than 90 degree.
- **Retrograde** orbits are those with inclination angle greater than 90 degree.

Inclination Angle of Orbit



Prograde Orbit

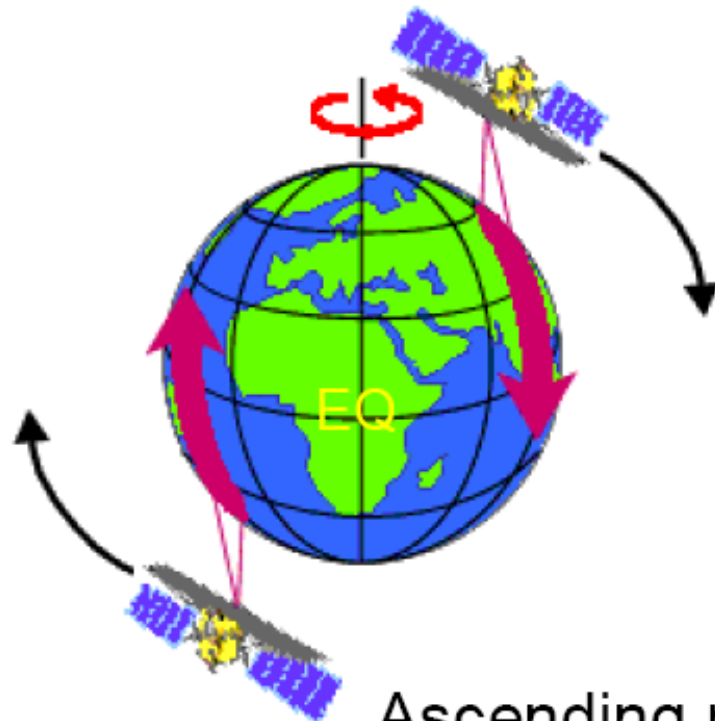


Retrograde Orbit

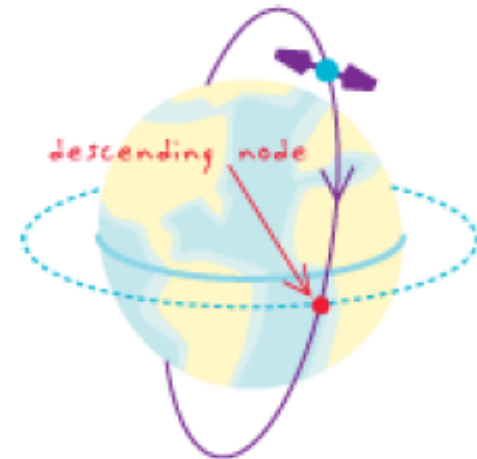
In ascending mode, measured CCW from equator.

Ascending and Descending

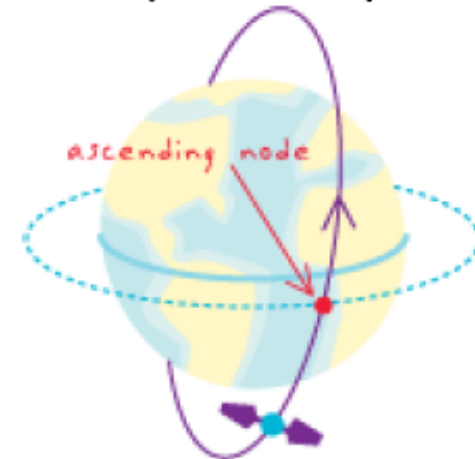
Descending pass



Ascending pass



Node = point that satellite crosses equatorial plane.



Orbital Elements

- The **classical orbital elements** are parameters for the location of a satellite in space, including **satellite position relative to the Earth** and the **orbital position**.

TABLE 2.1. Classical Orbital Elements

<i>Element</i>	<i>Symbol</i>
Semimajor axis	a
Eccentricity	ϵ
Inclination	i
Argument of perigee	ω_c
Right ascension of ascending node	Ω_1
Mean anomaly	M
Epoch time	t_0

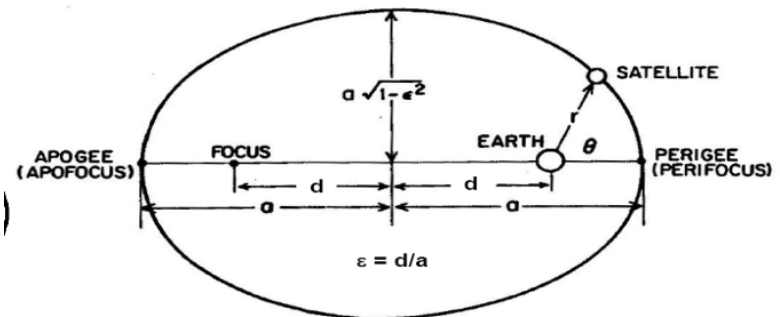


FIGURE 2.2. Elliptical orbit geometry.

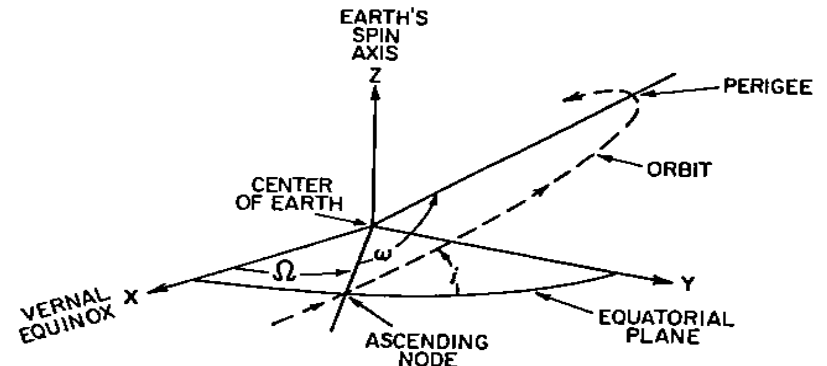
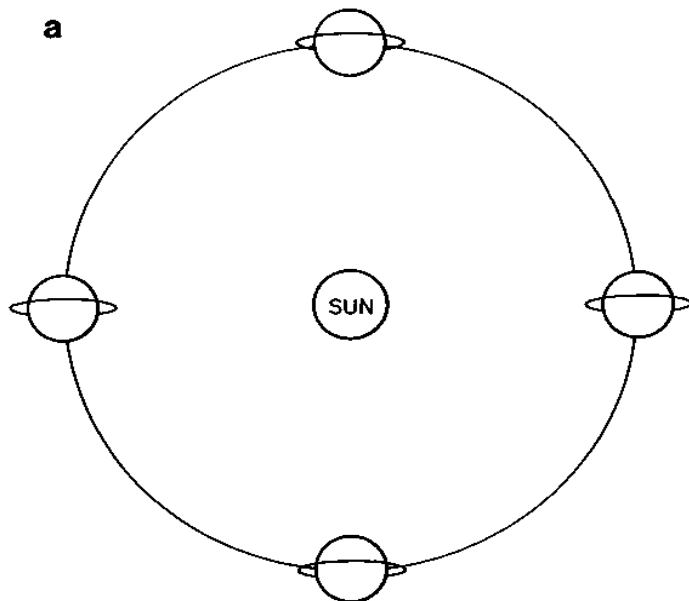


FIGURE 2.6. Angles used to orient an orbit in space.

- Mean anomaly:** is related to the true anomaly θ and eccentricity ϵ .
- Epoch time:** the time when these elements are observed or are “valid”.

Keplerian Orbits

- Keplerian orbits are orbits in which the classical elements (except mean anomaly M) are constant.
- The satellite moves in an elliptical path with the center of the Earth at one focus.
- The ellipse maintains a constant size, shape, and orientation with respect to the Sun.



***Keplerian orbit
viewed from space***

Keplerian orbit viewed from the Earth

- For orbits with period less than a day and the inclination angle greater than the latitude of the viewing point, the rotation of the Earth results in two daily passes of the satellite near the viewing point.
- One pass is descending, and the other is ascending. This usually means that one pass occurs during daylight and one during darkness.

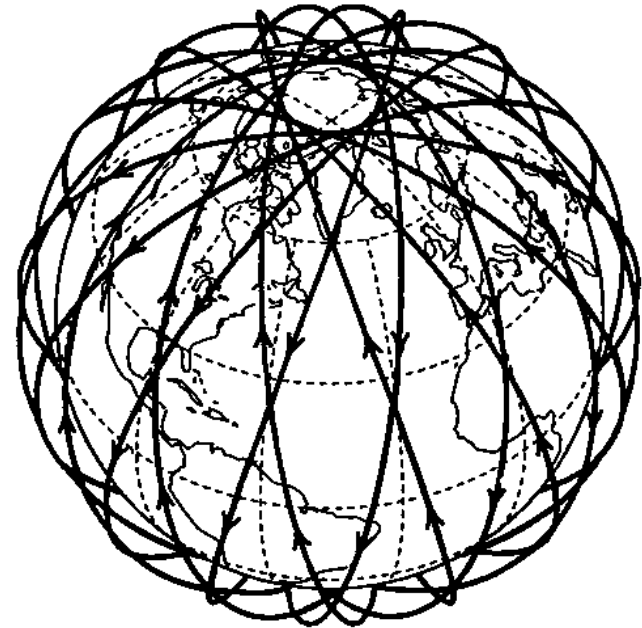


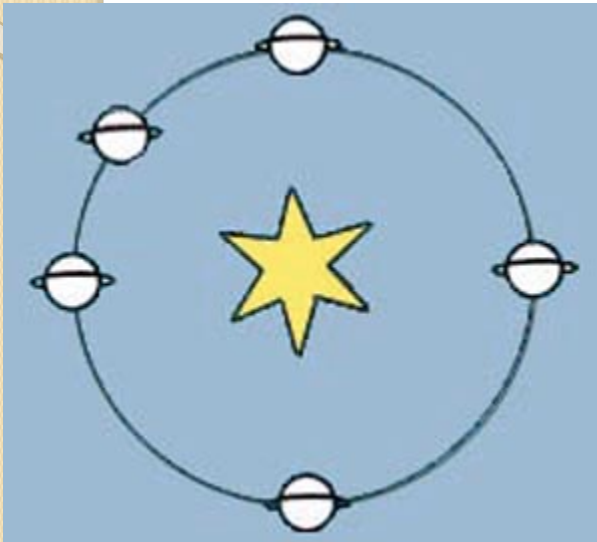
Fig. 2.8. The Keplerian orbit of a satellite as viewed from a point rotating with the Earth.

Meteorological Satellite Orbits

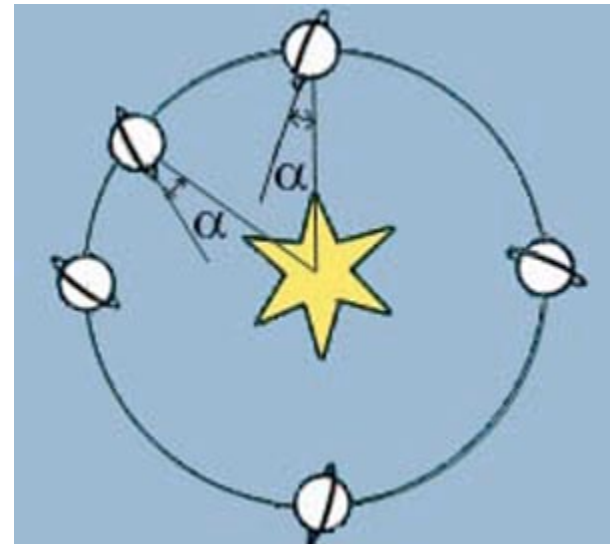
- **Sunsynchronous Orbit:** the orbit that is synchronized with the sun. The satellite crosses the equator at the same local time.
- **Geostationary Orbit (GEO):** synchronized with the Earth. At very high altitude (~35,000 km above Earth).
- Nearly all present meteorological satellite are in either sunsynchronous or geostationary orbit.
- However, sunsynchronous and geostationary are only two of infinite possible orbits.
- **Other Orbits** are also useful and will become more useful for meteorological satellites. For example, **Low Earth Orbit (LEO)**, **polar orbit (or near-polar orbit)**, and **equatorial orbits**.

Why using sun-synchronous orbits instead of Keplerian orbits?

Keplerian orbit change with season



sun-synchronous orbit change with season



The orbital plan is fixed while the Earth rotates around the sun. This causes the satellite to pass over an area at different times of the day. For example, if the satellite passes near noon and midnight in the spring, it will pass over near 6 am & 6pm in the winter.

Problems: 1) the data do not fit into operational schedules; 2) orientation of solar cell panel is difficult; 3) dawn or dusk visible images may not be as useful as images made at other times.

The orbital plan rotates with the Earth so that it makes a constant angle with the Earth-Sun direction.

Sunsynchronous Orbits

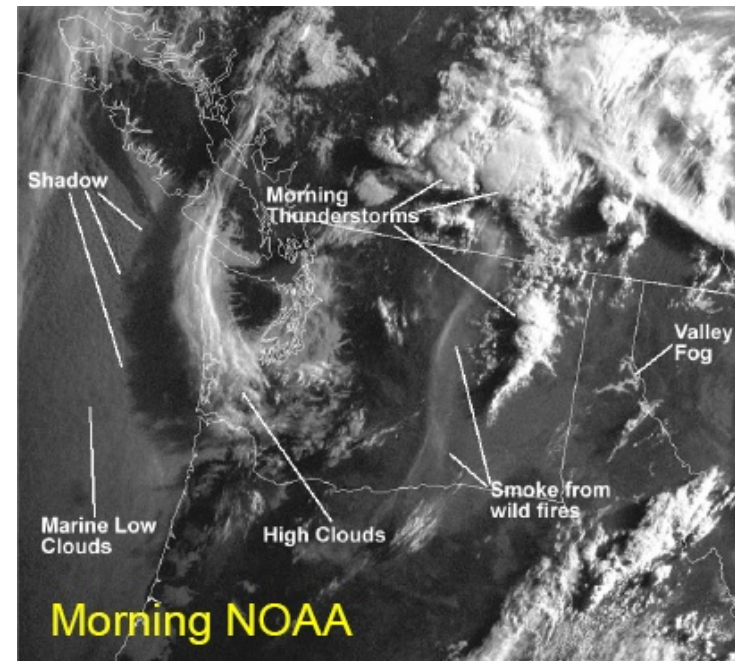
- A sun-synchronous orbit is synchronized with the sun and provides consistent lighting of the Earth-scan view. The satellite passes the equator at the same time each day.
- The orbital plane of a sun-synchronous orbit must also precess (rotate) approximately one degree each day, eastward, to keep pace with the Earth's revolution around the sun.
- Since sunsynchronous orbits reach high latitudes, they are referred to as **near polar orbits** (or **polar orbits** for short).
- Polar orbits are also called **low Earth orbits (LEOs)** to distinguish from **geostationary orbits (GEOs)**.
- **Sunsynchronous orbits** must be polar orbits and LEOs, but the converse is not necessarily true.

How to keep an orbit sun-synchronized?

- The Earth makes one complete revolution about the sun (2π radian or 360 degree) in one tropical year. Thus, the right ascension of the sun changes at the average rate of about 1 degree per day.
- If we can make the rate change of the right ascension of the satellite's ascending node as same as the rate change of the right ascension of the sun, then the orbit will be sun-synchronized, which means that the satellite crosses the equator at the same local time ($LT = UTC + \text{longitude}/15 \text{ degree}$) every day.
- The nonspherical gravitational perturbation of the Earth actually causes a rate change of the right ascension of ascending node as a function of inclination angle (i), semimajor axis (a), and eccentricity (ϵ).
- Therefore, we can adjust i for a specific a to make the orbit sun-synchronized. For example: for a satellite with $a=7228 \text{ km}$, $\epsilon=0$, $i=98.8$ degree will make it sun-synchronized.

Classification of Sun-synchronous Orbits

- **Sun-synchronous satellites** are classified by their Equator crossing time (ECT).
 - **Noon satellites (or noon-midnight satellites):** ascend & cross equator near noon local time (LT). Therefore, they must descend near local midnight.
 - **Morning satellites** ascend between 06-12 h LT and descend between 18-24 h LT.
 - **Afternoon satellites** ascend between 12-18 h LT and descend between 00-06 h LT.



Characteristics of Sun-synchronous Orbits

- **Advantages** of Sun-synchronous orbits:
 - 1) Low Earth orbits have good ground resolution.
 - 2) Polar orbiting at 700-900km altitudes permits both a large ground swath, offering a daily global coverage, and a good ground resolution. Most of the Earth observing missions use sun-synchronous satellites in low near polar orbits.
- **Limitations:** A continuous temporal observation is not possible with only one sun-synchronous satellite. It passes over polar regions on every orbital period, but much more rarely over equatorial regions (2 times a day for most current meteorological satellites; more generally it depends on the drift and the ground swath). A possibility to ease this difficulty could be to use a constellation of satellites (NASA GPM, launched in Feb. 2014).

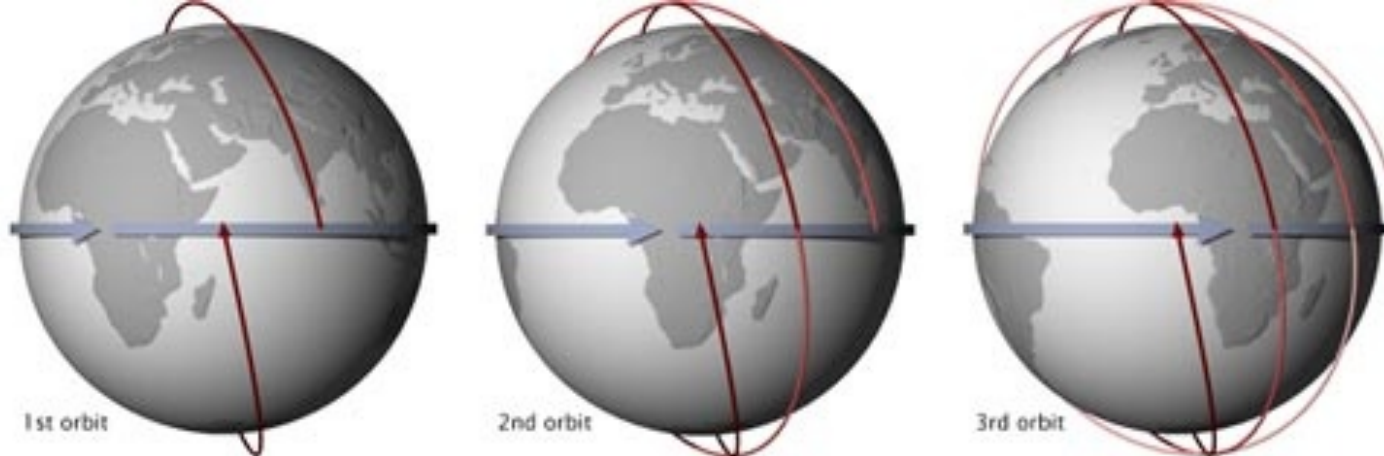
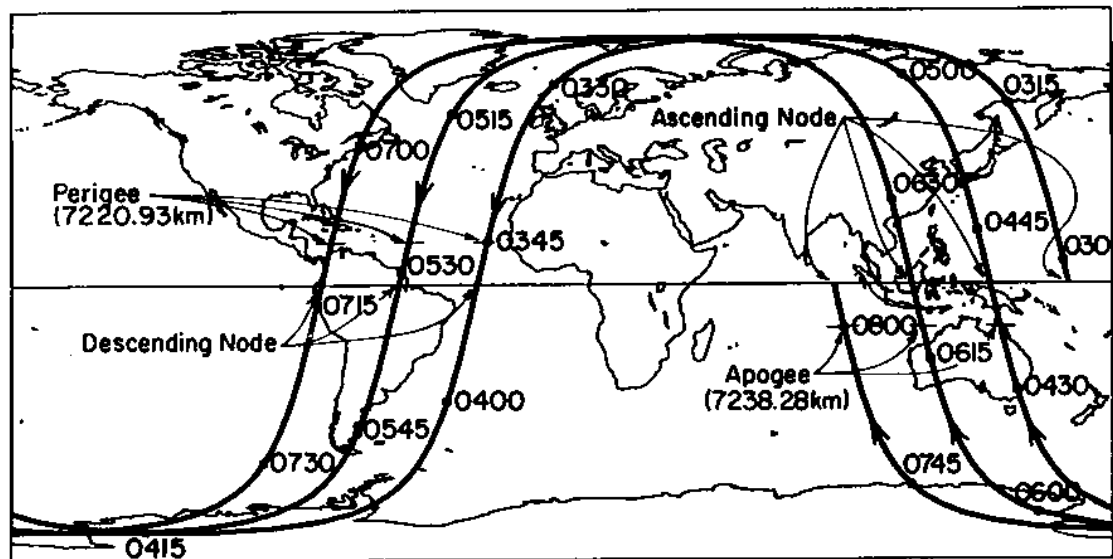


Illustration of the path of a sun-synchronous polar orbit. Image from NASA Earth Observatory.

NOAA II

Three Orbits on 22 March 1990

Start time: 0258 UTC End time: 0804 UTC



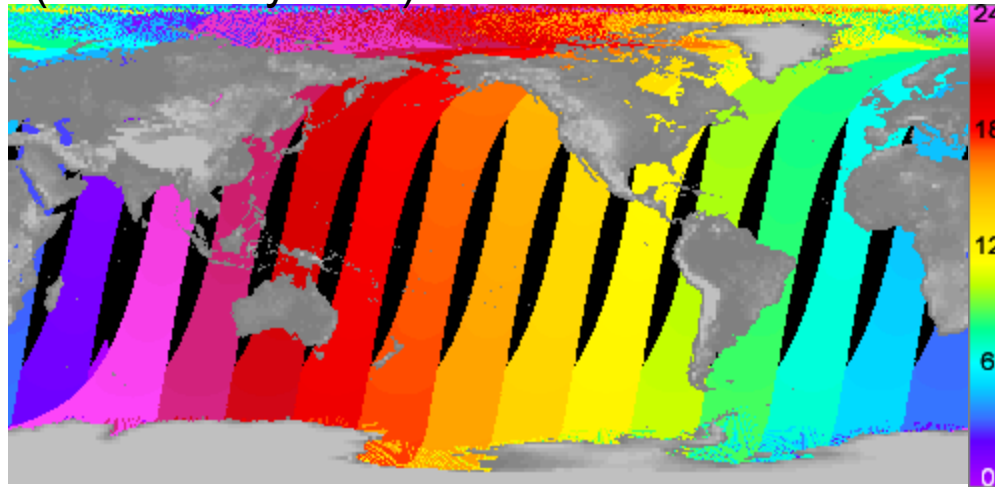
$a = 7229.606 \text{ km}$
 $i = 98.97446^\circ$
 $e = 0.00119958$
 $M_0 = 192.28166^\circ$

$\Omega_0 = 29.31059^\circ$
 $\omega_0 = 167.74754^\circ$
 Epoch time = 22 Mar 1990 1^h 15^m 52.353^s UTC
 Nodal Period = 102.0764 min

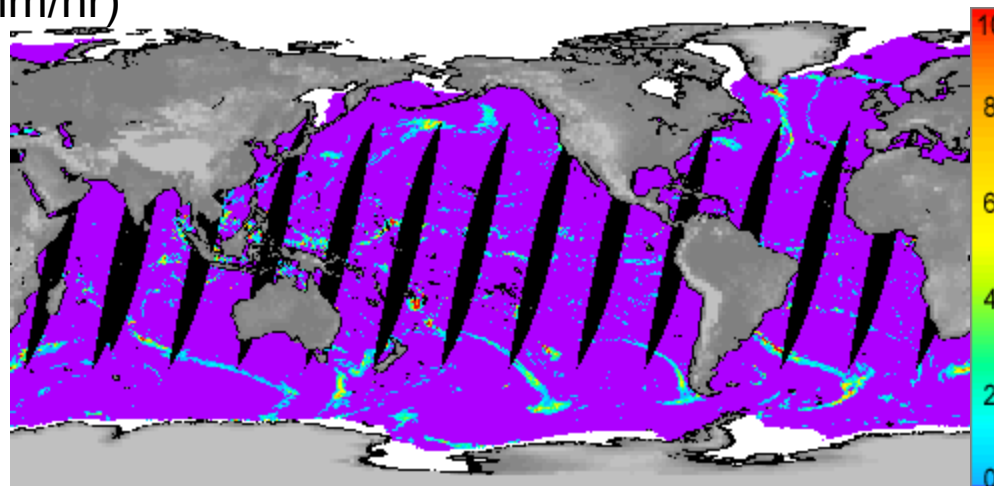
FIGURE 2.9. The ground track of a typical sunsynchronous satellite.

SSMIS (microwave instrument) on DMSP satellites (sunsynchronous, 14 overpasses per day) Local Morning Passes on Mar. 24, 2011

Observation Time (hour of day UTC)



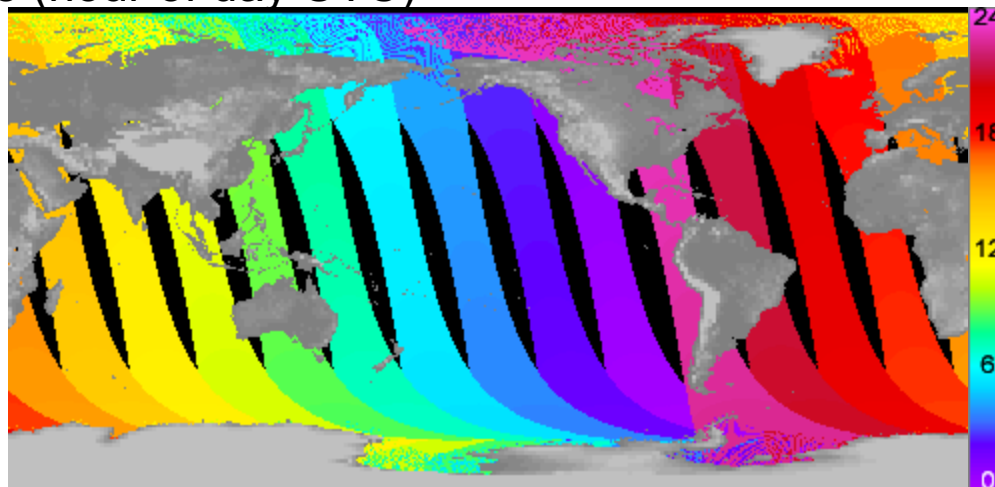
Rain Rate (mm/hr)



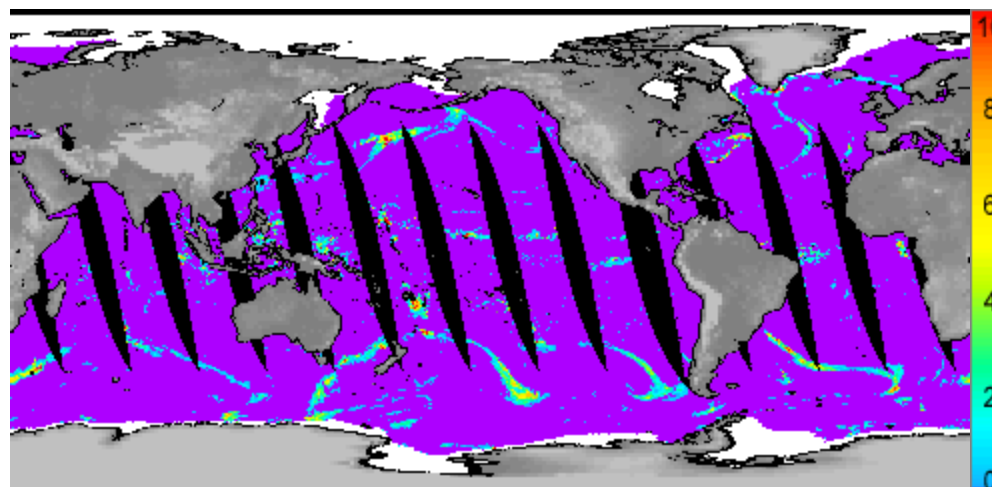
SSMIS (microwave instrument) on DMSP satellites (14 overpasses per day)

Local Evening Passes on Mar. 24, 2011

Observation Time (hour of day UTC)



Rain Rate (mm/hr)

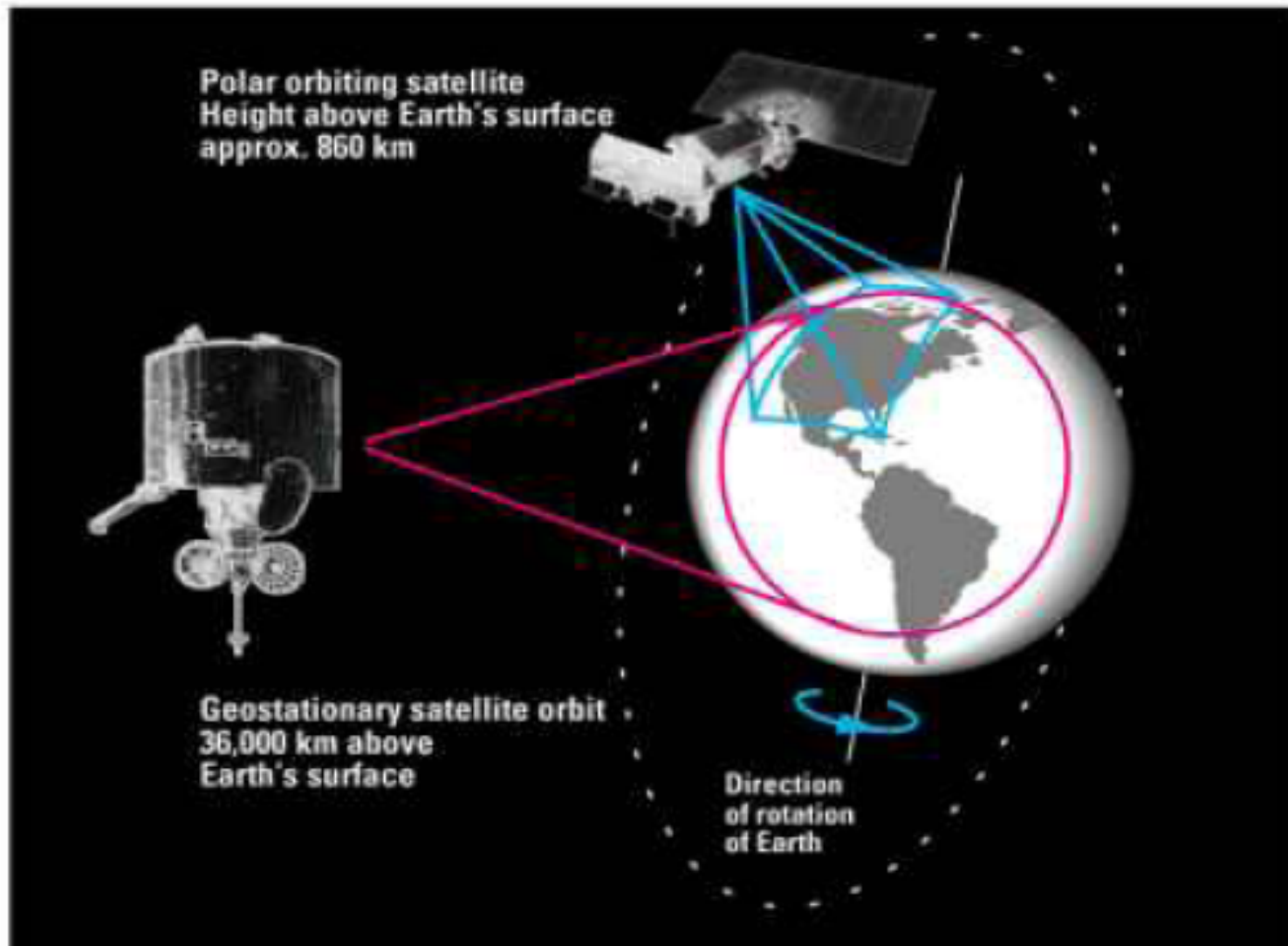


Geostationary Orbits

- *Geosynchronous* means that the satellite orbits with the same angular velocity as the Earth.
- **Geostationary (GEO)** orbit is geosynchronous, but it is also required to have zero inclination angle (around equator) and zero eccentricity (circular).
- The geostationary satellites (GEOs) circle the Earth in a geostationary orbit above the equator which means that they hover continuously over one place on the Earth's surface.
- Video:

<http://www.hurricanescience.org/science/observation/satellites/geostationary/>

Polar vs Geostationary View



Geostationary Satellite
35,800 km altitude

mean distance to moon = 384,400 km

17.4°



earth radius = 6,370 km

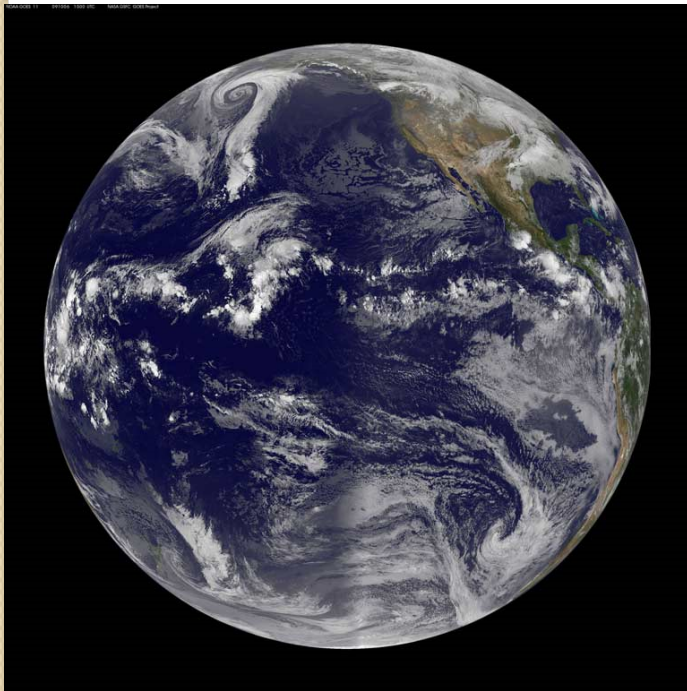
typical shuttle orbit = 225 – 250 km

Hubble Space Telescope = 600 km

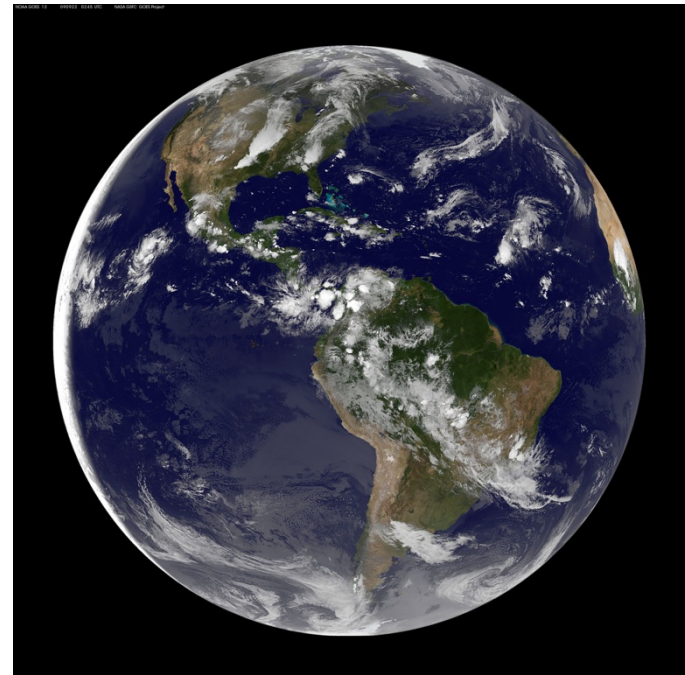
110.8° **Polar Orbiting Satellite**
850 km altitude

US GOES Satellites

- GOES (geostationary operational environmental satellites) East: over the US east coast.
- GOES West: one over the US west coast.
- Between them they can provide images for the whole U.S.
- Future GOES-R (2015): higher spatial and temporal resolution.

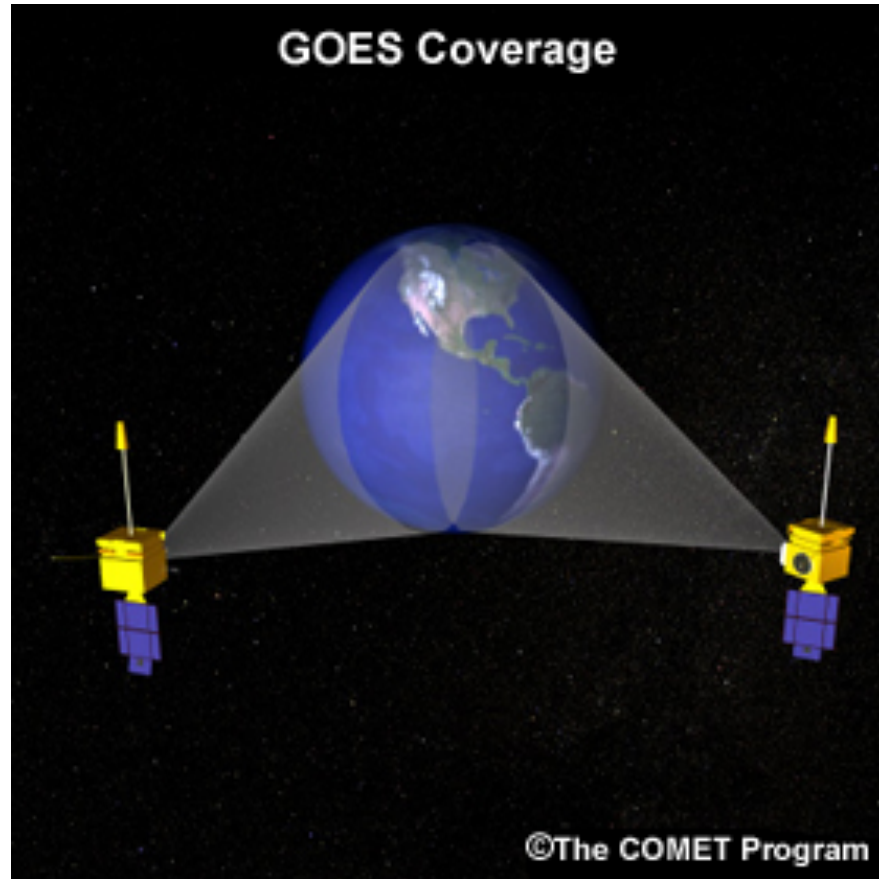


Full-disc view from GOES west.



Full-disc view from GOES East.

GOES US coverage



Facts for Geostationary Orbits

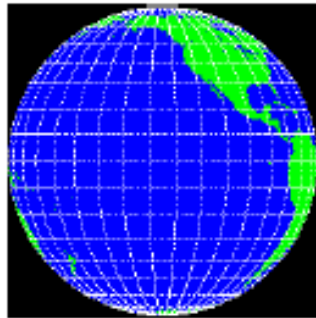
1. **Continuous observation and high temporal resolution:** Since the field of view of a satellite in geostationary orbit is fixed, it always views the same geographical area, day or night. This is ideal for making regular sequential observations of cloud patterns over a region with visible and infrared radiometers. **High temporal resolution and constant viewing angles** are the defining features of geostationary imagery. Good for diurnal variation studies.

2. **Spatial resolution:** Geostationary satellites sensors are most useful for tracking atmospheric features over great distances because of their high temporal resolution (15 – 30 minute intervals) and hemispheric field of view . However, the orbital distance of the satellites means that **their spatial resolution is less than optimal for the identification of features smaller than 1km.**

Views of Operational Geostationary Satellites



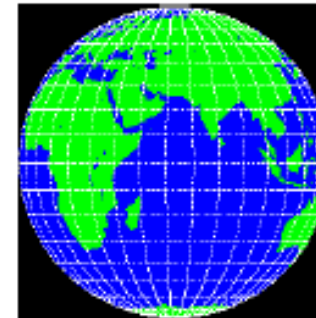
GOES-E 75° W



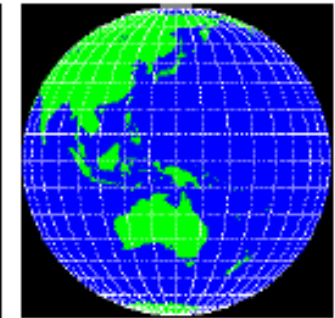
GOES-W 135° W



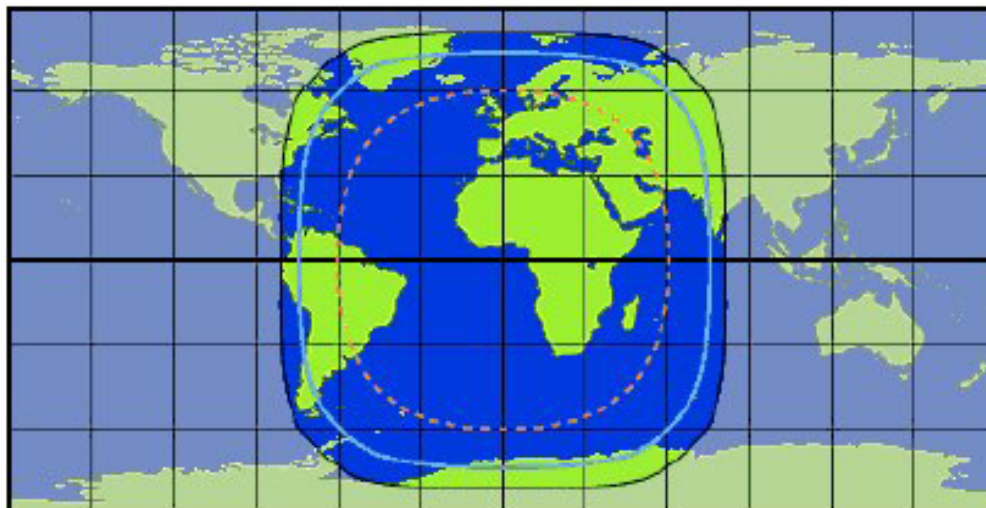
METEOSAT 0° W



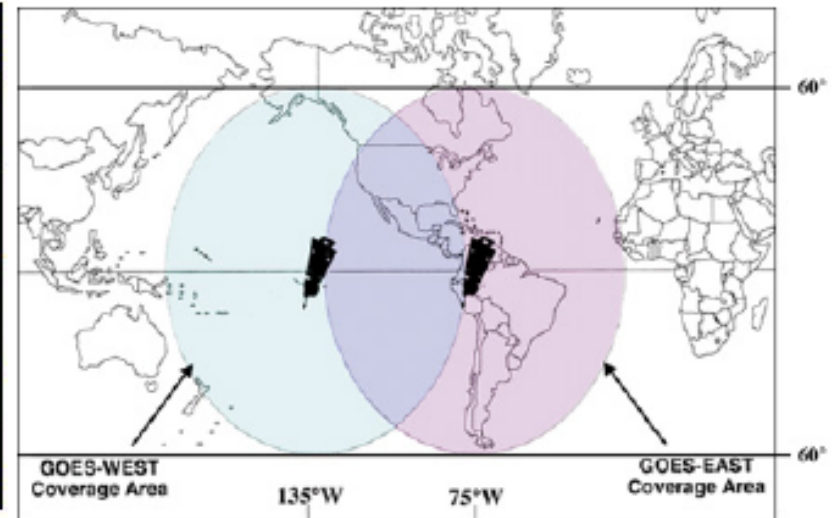
INSAT 63° E



GMS 140° E



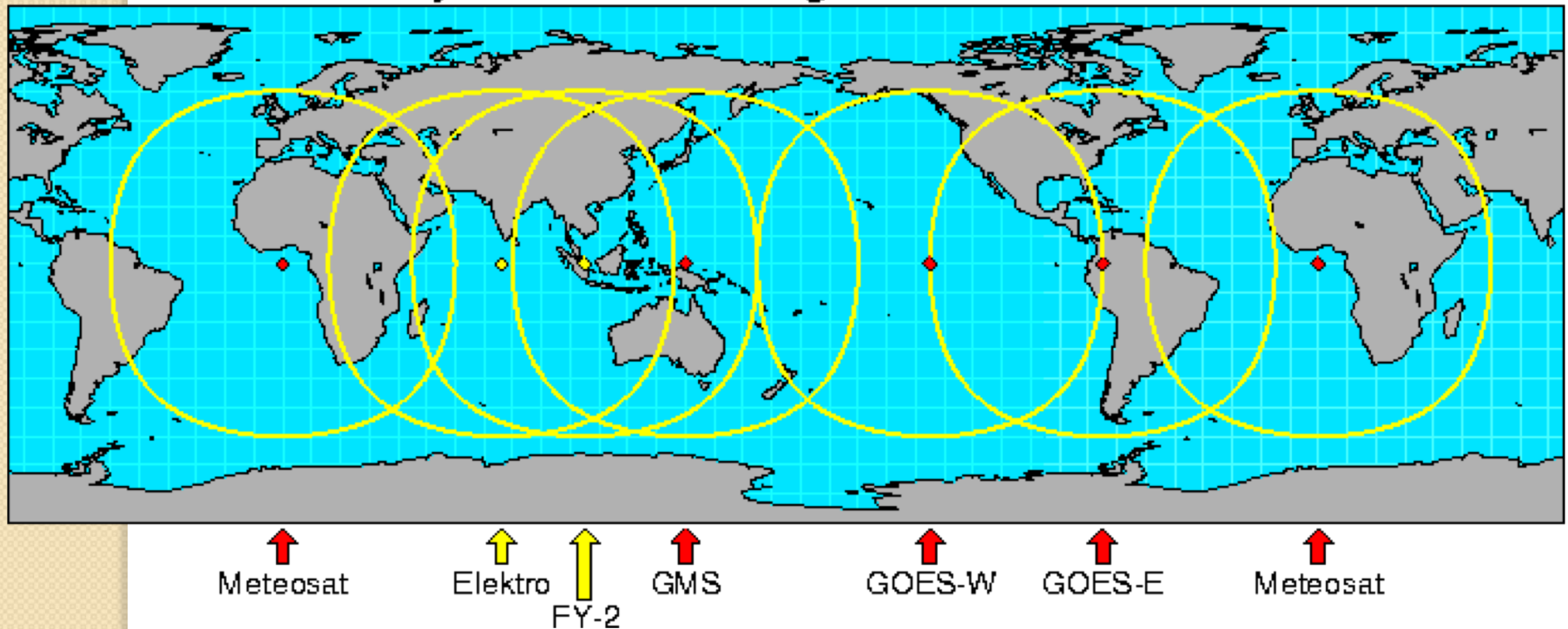
- Maximum theoretical coverage
- Imaging and telecommunications coverage
- - - Meteosat images within this area used quantitatively



Quantitative coverage ~ 60N to 60S

Geostationary Satellite Coverages

Global Geostationary Satellite Coverage



Other Orbits

- **Low Earth Orbit (LEO):** the orbit that is 200 to 1200 km above Earth (to distinguish from GEO).
- **Polar Orbit** (or near-polar orbit): Any LEO that reaches high latitude.
- **Equatorial Orbits:** Low inclination angle, thus orbits near the equator.

Polar Orbits: $i \approx 90^\circ$

- Polar orbiting satellites are launched into orbits at high inclination angles, such that they pass across high latitudes near the poles. Most polar orbits are circular to slightly elliptical at distances ranging from 700 to 1700 km (435 - 1056 mi) from the Earth. At different altitudes they travel at different speeds.



Fig. 1. Example of a Near-Polar Orbit.

The ground track of a polar orbiting satellite is displaced to the west after each orbital period, due to the rotation of the Earth. This displacement of longitude is a function of the orbital period (often less than 2 hours for low altitude orbits).

Fig. 2. Map of the ground path of one revolution of a typical near-polar orbiting satellite.

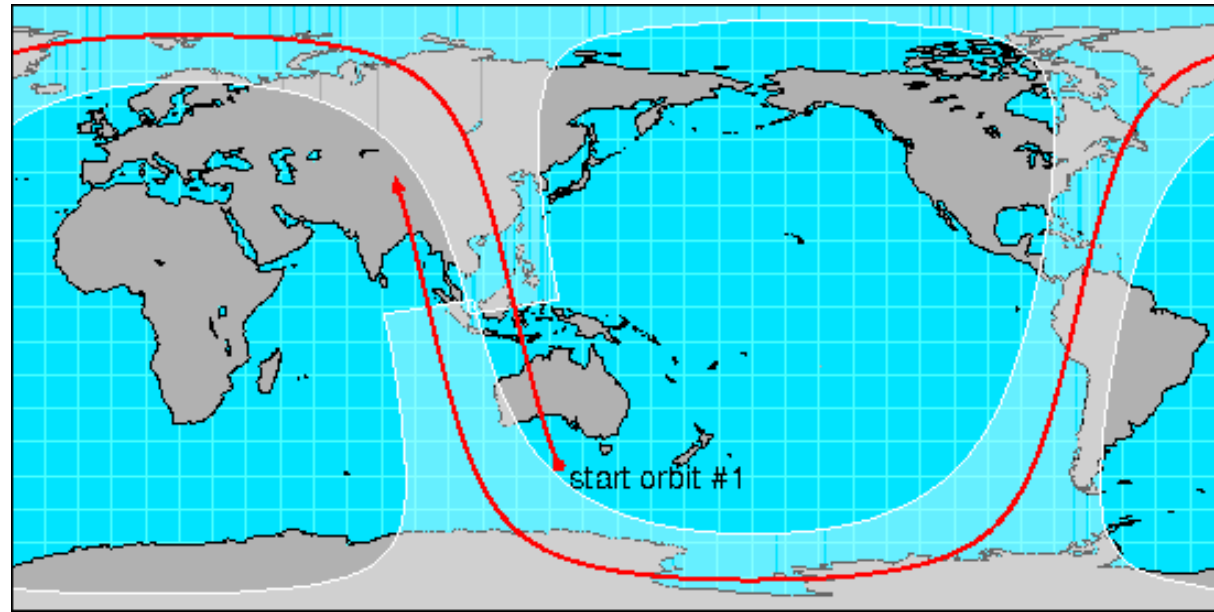


Fig. 3. The orbit of a near polar satellite as viewed from a point rotating with the Earth.

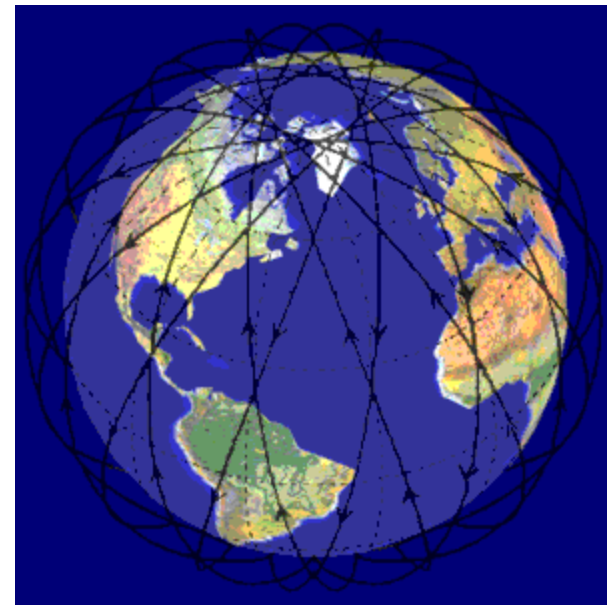
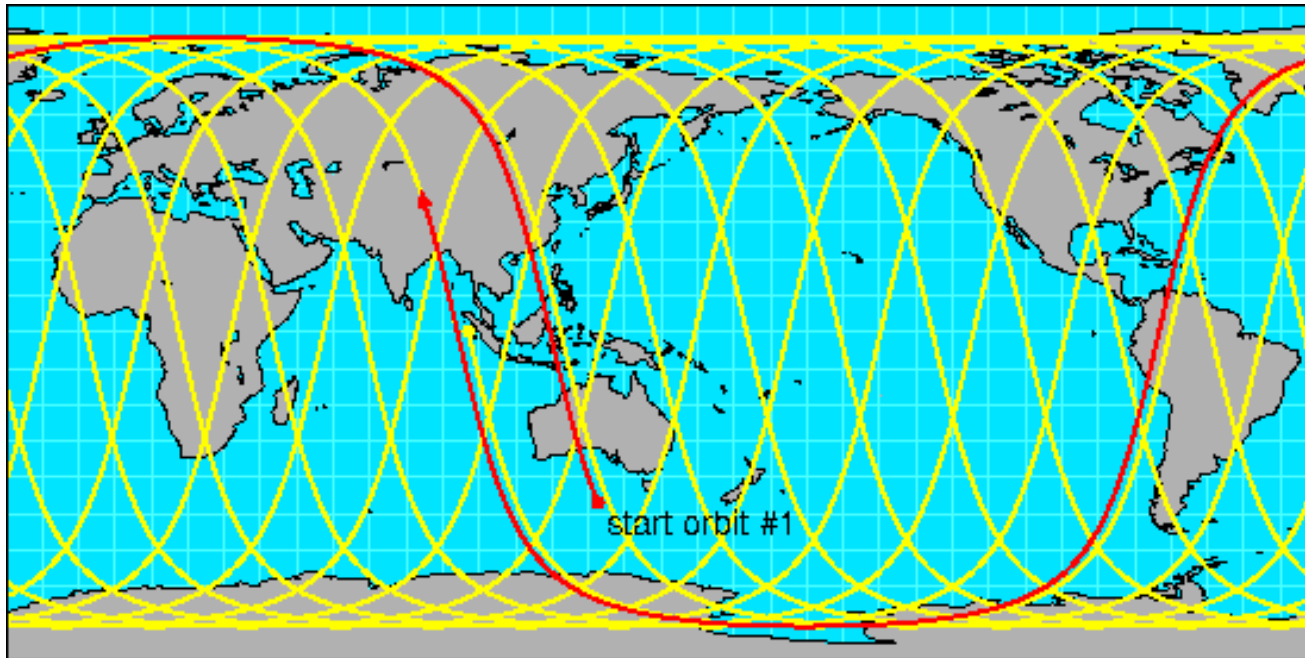
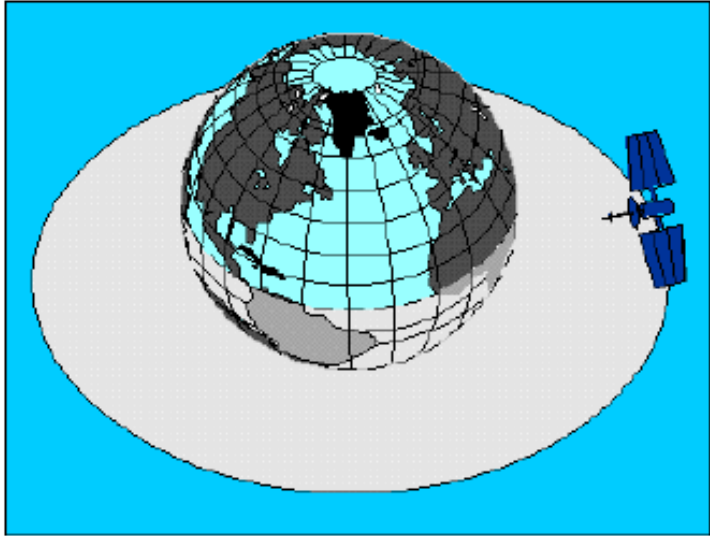
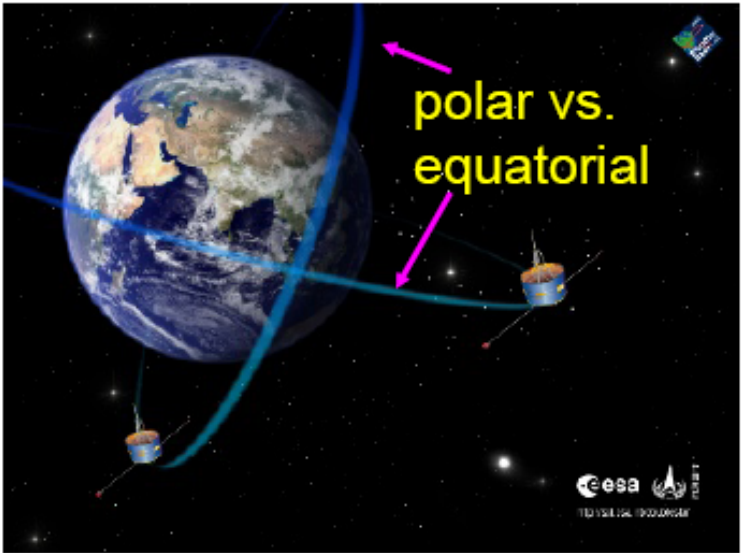


Fig. 4. The ground paths of the multiple orbital revolutions during one day for a near-polar orbiting satellite.

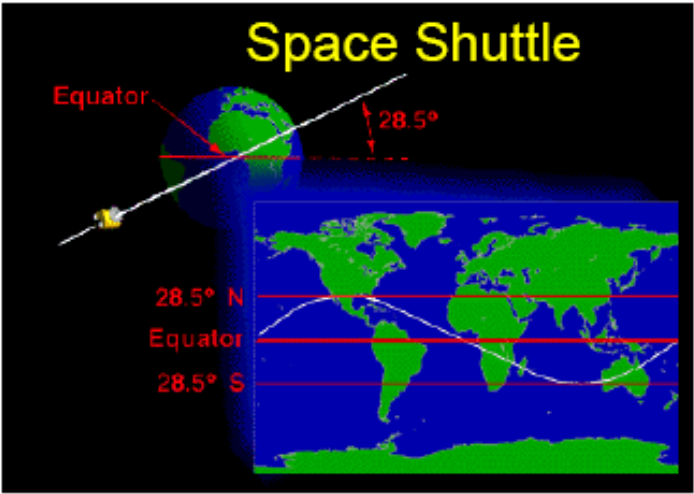


Depending on the ground swath of the satellite, it is possible to adjust the period (by varying the altitude), and thus the longitudinal displacement, in such a way as to ensure the observation of any point on the Earth within a certain time period. Most of the near polar meteorological satellites ensure complete global coverage of the Earth, during one day, thanks to a ground swath of about 3300 km.

Equatorial Orbits: Low inclination angle, thus orbits near the equator.



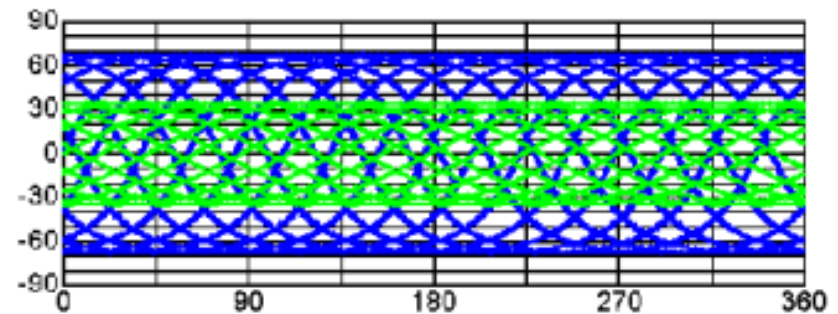
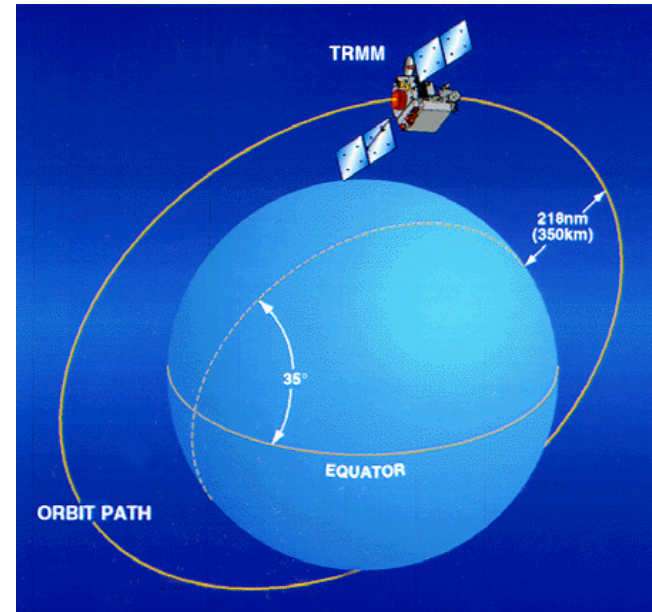
equatorial orbit



NASA's TRMM, $i = 35^\circ$

NASA's Tropical Rainfall Measurement Mission (TRMM) Satellite

- Launched in Dec. 1997.
- 16+ years (1998-current) of data available, very unique dataset for precipitation and convection studies in tropics
- TRMM satellite orbit: LEO, equatorial, circular, Non-Sunsynchronous)
- Altitude: 350 km (402 km since Aug. 2001)
- Inclination: 35 degree.
- Observation frequency: 16 times per day.
- TRMM flies over each position on the Earth's surface at a different local time each day. So it is good for diurnal variation studies.



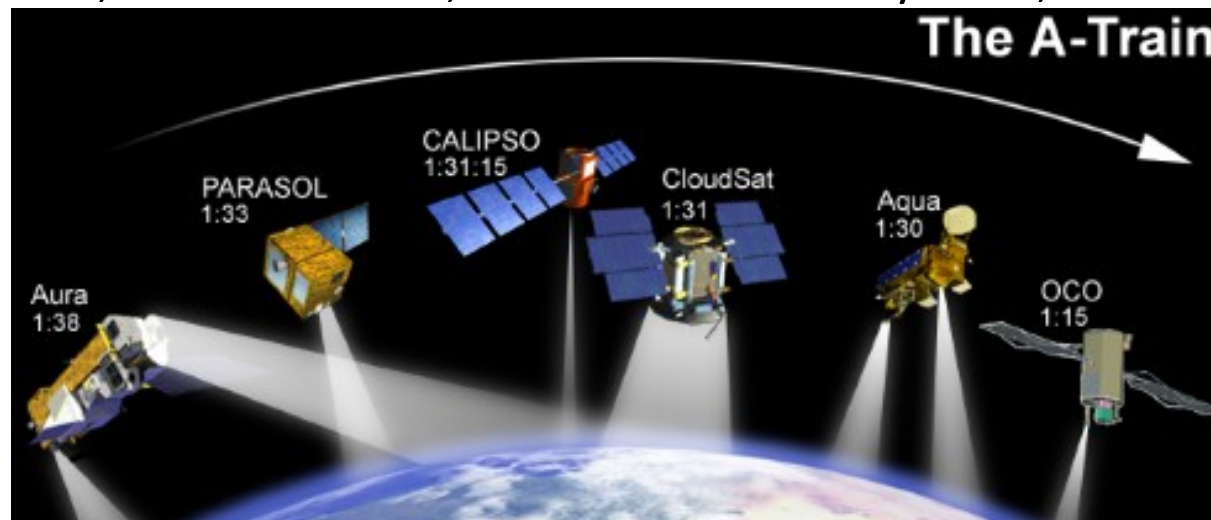
Blue: Inclination ~65° (GPM core)
Green: Inclination ~35° (TRMM)

- TRMM Movie
- -- Animation of TRMM orbit

<http://earthobservatory.nasa.gov/Library/TRMM/>

NASA's A-Train Satellites

- The **A-train** (from **Afternoon Train**) is a satellite constellation of six satellites in sun-synchronous orbit at an altitude of 690 kilometers above the Earth. The orbit, at an inclination of 98.14° , crosses the equator each day at around 1:30 pm solar time, and crosses the equator again on the night side of the Earth, at around 1:30 am. They are spaced a few minutes apart from each other so their collective observations may be used to build 3D images of the Earth's atmosphere and surface.
 - Aqua, launched in 2002.; land cover, land cover change, and atmospheric constituents
 - Aura, 2004; Ozone, air quality, etc.
 - CloudSAT, CALIPSO and PARABOL : 2006; clouds and aerosols
 - OCO-1, failure in 2009; OCO-2 launch in July 2014; measure CO₂



- Animation of A-Train orbit

<http://sci.gallaudet.edu/MSSDScience/a-trainanimation.mpg>

Satellite Instruments

Instruments are sensors on board satellites. Meteorological observations are taken by instruments.

For example,

Instrument	Satellite
PR	TRMM (Equatorial orbit)
TMI	TRMM
SSM/I	DMSP F14 (sun-syn.)
SSM/I	DMSP F15 (sun-syn.)
CPR	CloudSat (sun-syn. circular, 705km)
MODIS	Terra (sun-syn. circular, 705km)
MODIS	Aqua (sun-syn. 1:30pm ECT)
SeaWinds orbit)	QuikSCAT (Sun-syn., 803 km, 98.6° inclination
NSCAT/SeaWinds	ADEOS (Sun-syn.)