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<u>Remote Sensing of the Atmosphere and Ocean</u>

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Lecture 1. Satellite orbits

References: Kidder and Vonder Harr chapter 2, Stewart chapter 15.

Physics of satellite orbits

Kepler:

1. Planets move in elliptical orbits with the sun as one focus
2. the radius vector from sun to planet sweeps out equals areas in equal times
3. $T^2 : R^3$ ratio is constant for all planets

Substitute satellite for planet and earth for sun in the above rules and they apply for artificial earth satellites.

Newton:

$$F = ma = m\frac{dv}{dt}$$

Gravity

$$F_{gravity} = \frac{GMm}{r^2}$$

where r is the separation of the two masses M and m

$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}

$M_{earth} = 5.976 \times 10^{24}$ kg

An object of mass m falling in the earth's gravitational field at the earth's surface accelerates at a rate determined by

$$ma = \frac{GMm}{r_{earth}^2}$$

$$a = g = \frac{GM_{earth}}{r_{earth}^2}$$

$r_{earth} = 6373$ km

(Note: this is independent of mass m - remember Galileo)

$g = 9.81$ m s^{-2}

A satellite in permanent Keplerian orbit maintains a balance between gravity and centripetal force due to its circular motion.

Centripetal acceleration = $\frac{v^2}{r}$

v is the speed of the satellite
r the radius of the orbit

Gravity balancing centripetal force for a circular orbit means that:

$$\frac{GMm}{r^2} = \frac{mv^2}{r}$$

$$v = \sqrt{\frac{GM}{r}}$$

v does not depend on *m*

Altitude of the satellite determines its orbital period

$$vT = 2\pi r$$

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

$$T = 2\pi\sqrt{\frac{r^3}{GM}}$$

The ISS at altitude 360 km *above the earth surface* will have a period of

$$T = 2\pi\sqrt{\frac{(6373+360)^3 x 10^9}{3.986 x 10^{14}}}$$

$$= 5.498 x 10^3 \; s$$

or 91.6 minutes at a speed of 7.69 x 10^3 m s^{-1} = 17,200 mph

Geometry of elliptical orbits

Figures from Kidder and Vonder Haar (their figs 2.4,2.5) and Stewart (his figs 15.1, 15.3)

Orbit shape is defined by its *eccentricity (e), semi-major axis (a)*

Satellite position is defined in polar coordinates: r, θ $\quad r = \frac{a(1-e^2)}{1+e\cos\theta}$ where angle θ is called the *true anomaly* and is measured counterclockwise from *perigee*

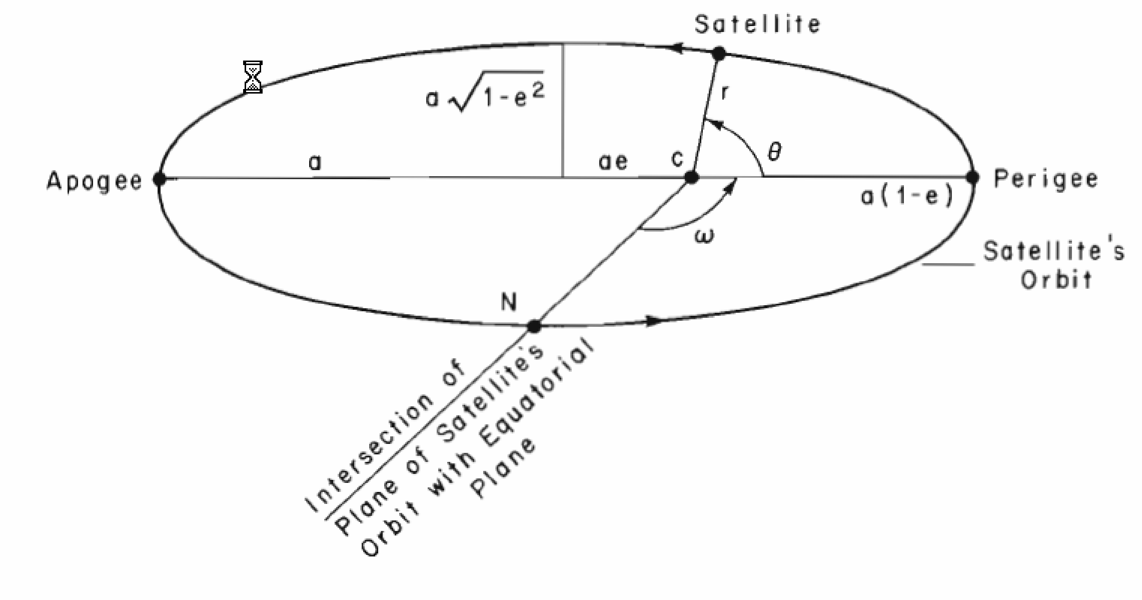


Figure 15.3 Coordinates and notation for describing an elliptical orbit.

(from Stewart)

Lecture 2. Orbits (continued) and measurement geometry

The location of the orbital plane is defined with respect to an inertial coordinate system – i.e one that is independent of the earth's rotation.

The Earth's rotation does not affect the satellite orbit, but does affect how the satellite's field of view samples the land, ocean, and atmosphere phenomena we are observing.

Right-ascension-declination coordinate system

z-axis parallel to Earth rotation axis (north pole – south pole)

x-axis toward point on the celestial sphere when the sun is at the vernal equinox (21 March). So x-axis lies in both the *ecliptic* and the satellite's *orbital plane*

Satellite orbit is described by 3 angles:

i = inclination = angle between orbital plane Earth's equatorial plane

$i < 90$ prograde; $i > 90$ retrograde

Ω = right ascension = angle from x-axis to ascending node N, where N is the location on the equator where the satellite crosses from south to north (on the *ascending* pass).

ω = perigee angle = angle in orbital plane between N and perigee

The satellite position θ is measured counterclockwise from perigee, unless the orbit is exactly circular, when it is measured from ascending node N.

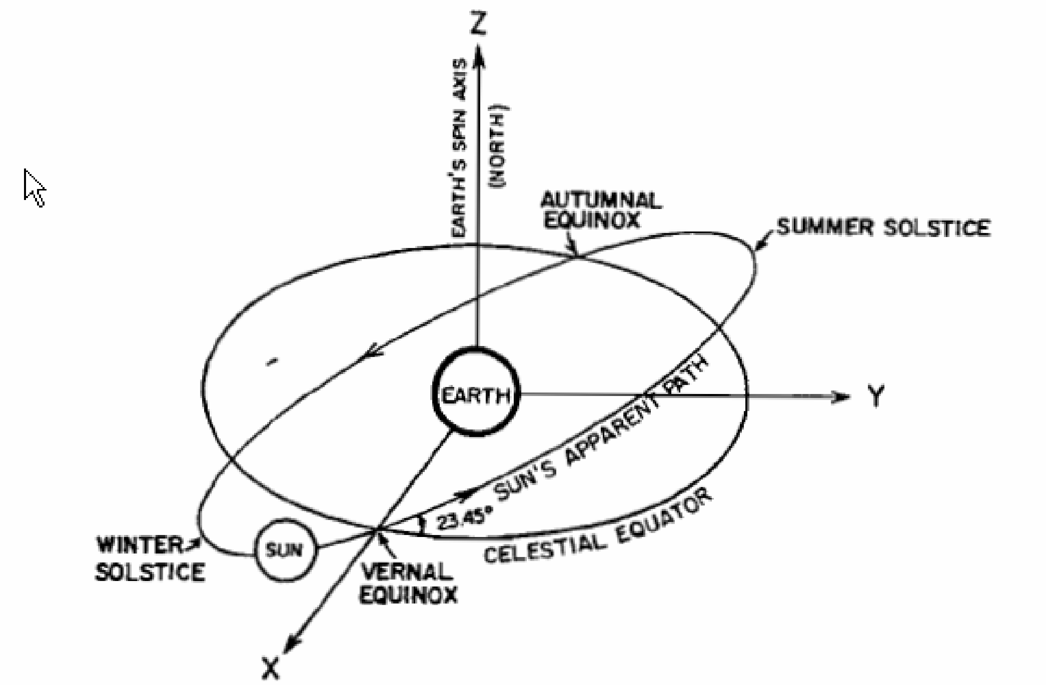


FIGURE 2.4. The right ascension–declination coordinate system.
(from Kidder and Vonder Haar)

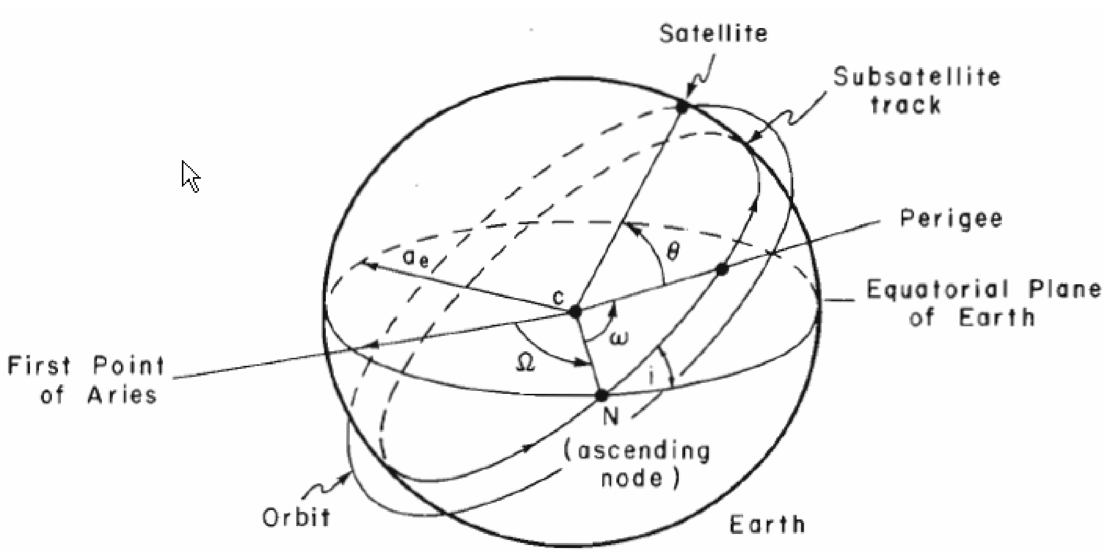
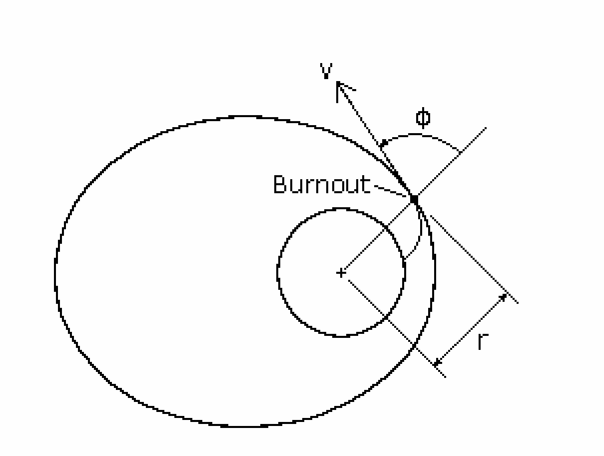


Figure 15.1 Coordinates for describing the orbit of a satellite orbiting around the Earth.

Launching into orbit

Launches are usually designed to place the satellite at perigee at the time of main engine cutoff. This requires the least energy.



Depending on operational requirements, a satellite may be maneuvered to another orbit by short burns of thruster rockets that the change the satellite velocity (speed and direction).

The launch sequence for a low earth orbit satellite would have

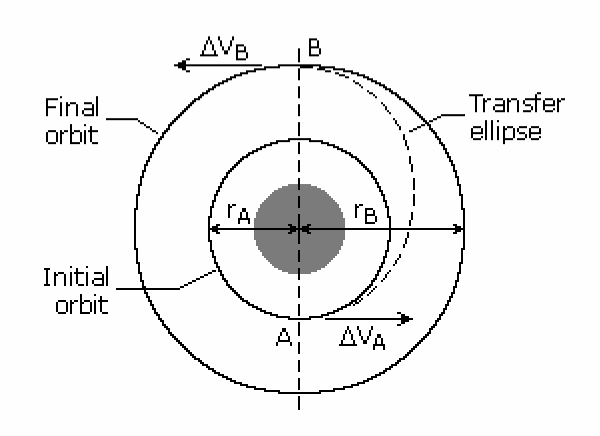
- main engine cutoff at around 5 minutes
- second stage at around 10 minutes
- fairing is typically jettisoned after second stage
- separation of satellite from the launch vehicle occurs after about 1 hour
- solar panel deployment, sensor deployment, activation of navigation, checks on pointing and nominal performance etc would proceed over the next 24 hours

- NOAA meteorological satellites weigh about 1500 kg, are about 5 m long x 2 m diameter, deploy a solar array 6 m long, and require 800 W power

View Topex/Poseidon launch (quicktime movie)

To boost altitude with the least effort uses a maneuver called a Hohmann Transfer

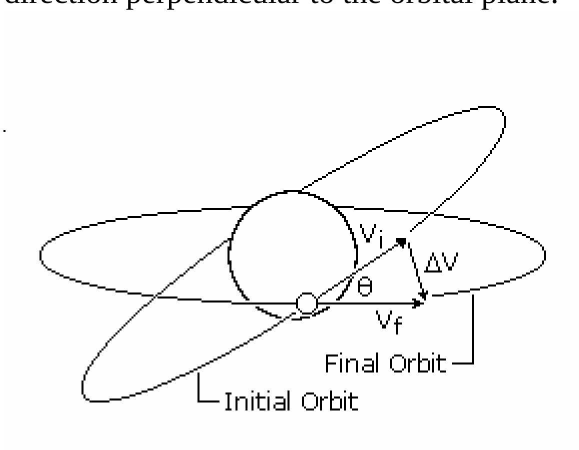
Added velocity Δv_A puts the satellite into an elliptical orbit. At apogee Δv_B puts the satellite into a final orbit at the new altitude.



The greatest initial velocity at liftoff occurs if the launch is due east, because this adds the rocket velocity to the maximum velocity due to the earth's rotation.

The launch site is always on a groundtrack, so this means a launch due east is into a prograde orbit with inclination the same as the launch site latitude. To reach a greater inclination, the satellite must be maneuvered out of this orbital plane (i = 28.5° for Cape Canaveral).

To change the inclination of the orbital plane of the satellite, thrust is required in the direction perpendicular to the orbital plane.



Placing a satellite into its final orbit is usually achieved by a sequence of brief thruster bursts designed to achieve specific changes in orbital plane and altitude.

Between each burst of thrusters the satellite moves freely in a Keplerian orbit. It is tracked precisely to compute the effect of the thruster burst, and subsequent maneuvers fine-tuned to achieve the desired outcome.

To rendezvous with another satellite, an orbit in the same plane is first achieved, but at a slightly lower altitude (to catch up) or higher altitude (to be caught).

Keplerian orbits are fixed with respect to the distant stars. This is because the orbit is a local balance of forces between gravity and centripetal force.

If the earth were not rotating, the ground-track would be a great circle.

But the earth is rotating, so the ground-track advances toward the west on each subsequent orbit.

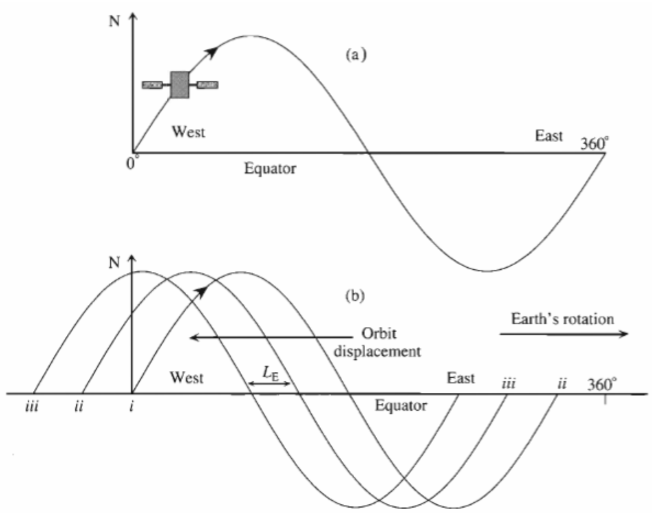
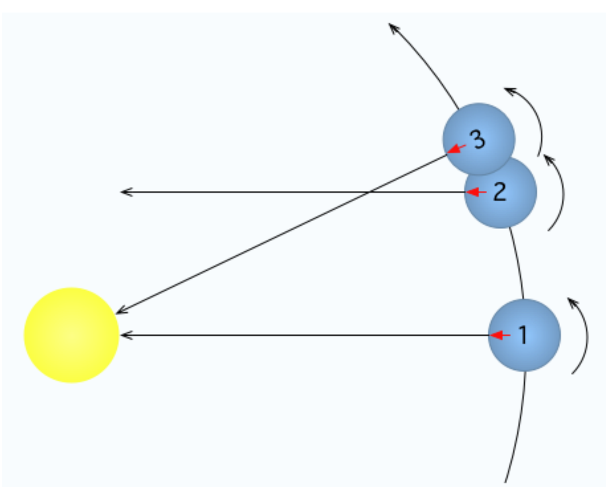


Figure 1.2. Mercator map of the satellite ground track for the orbit in Figure 1.1 and for (a) non-rotating Earth; (b) rotating Earth. See text for further description (Adapted from Elachi, 1987, Figure B-6).

The separation of equator crossings can be calculated from the period of the satellite and the speed of a point on the equator (circumference of the Earth divided by 1 *sidereal* day). If the earth circumference divided by the equator crossing separation is an integer, the satellite is in an *exact repeat orbit.*



In a Keplerian orbit the orbital plane remains fixed with respect to the distant stars (the inertial reference frame).

This is a problem for most earth observing systems because of the change in local observation time and the lack of an exact repeat of the ground-track.

The gravitational potential of the earth is not uniform because the distribution of mass in the earth is not exactly spherical.

$$V \approx -\frac{GM}{r}\left[1-\frac{r_{earth}^2}{r^2}\frac{J_2}{2}\left(3\sin^2\phi-1\right)\right] \qquad \text{(potential energy per unit mass)}$$

where J_2 is the spherical harmonic that contains most of the gravitational anomaly due to the equatorial bulge of the earth.

This irregularity causes a steady precession of the orbital plane about the z-axis at a rate:

$$\dot{\Omega} = -\frac{3}{2}J_2\sqrt{\frac{GM}{r}}\frac{r_{earth}^2}{r^3}\frac{\cos i}{(1-e^2)^2}$$

which depends on the satellite orbits *inclination, altitude* and *eccentricity*.

Sun synchronous orbits

The orbital parameters can be chosen so that the rate of precession of the ascending node is 360/365.25 degrees of longitude per 24 hours, in which case the orbital plane maintains a fixed angle with the line from the sun to the earth throughout the year.

The satellite passes overhead at the same local time every day.

The sun synchronous orbit with zero eccentricity has a semi-major axis of 7228 km and inclination of 98.8^o.

This is the orbit used by the NOAA "polar orbiting" meteorological satellites, NASA's Terra and Aqua satellites, and many more.

It is conventional to refer to satellite that ascend (past the equatorial nodal point) between 0600 and 1200 local time as *morning satellites,* and those that ascend between 1200 and 1800 local as *afternoon or evening satellites.*

This orbit does not go directly over the poles, so the satellite will not observe the polar region unless the field of view of the instruments on board is wide enough to see to the higher latitudes.

Geostationary orbits

Another way to observe the same point on the earth’s surface at the same time every day is to simply park a satellite directly overhead.

A satellite in the equatorial plane (zero inclination), zero eccentricity, and semi-major axis of 42,168 km has a period of 24 hours, and it said to be geostationary.

View satellites and their orbits at:
http://science.nasa.gov/realtime/jtrack/Spacecraft.html

Shows ground tracks and 3-D orbits for all satellites

Notice the clusters of satellites in the major categories or orbits

Geostationary, Polar orbiting (NOAA, Topex, ERS, Envisat), Low Earth orbit (Iridium, HST, ISS), GPS

Unusual orbits (especially ground track): Chandra, IMAGE, CRRES (in a geosynchronous transfer orbit)

Measurement geometry and imaging techniques

References: Martin, chapter 1.6.

Satellites use several methods to form an image.

Low earth orbit satellites typically use an instrument that has a small field of view (FOV) (designed for sensor accuracy, resolution, and efficient power use), and scan the sub-satellite path to form an image.

The wider the swath of the scan the more of the earth’s surface that can be imaged in a single pass.

Scan modes:

A ***whisk-broom*** scan mode is achieved with a rotating mirror to direct the observed radiation into a fixed detector

> calibration can be achieved by having the scanner view a fixed internal source on each spin, or a fixed point in space for a background value

A ***push-broom*** scan mode uses lens to direct observing from different view angles into different detectors.

Various strategies can be devised to image multiple wavelengths with multiple detectors if this is desirable.

Viewing a wide swath at different angles introduces issues that must be considered when forming a single image, calibrating, and interpreting the data.
For an optical sensor with a fixed solid angle FOV:

- view angle with respect to the sun affects the illumination of the surface, and the reflected vs emitted light
- scan angle alters the atmospheric path length and attenuation
- off nadir scan angle makes the ground point imaged an ellipses of increasing size and eccentricity as the scan angle increases

Conical scan

A fixed scan angle can be achieved with a conical scan

(but will still have different solar angle relative to the earth)

The conical scan can image the same point twice (looking fore and aft) which means two measurements of the same place are made through different atmospheric paths, which can be used to aid in the correction of atmospheric effects.