SATELLITE COMMUNICATION
Ref Book


Satellite is a system that supports mobile communications.

It offers global coverage without **wiring costs** for base stations and is almost independent of varying **population densities**.

Two or more stations on Earth
- Called ‘Earth Stations’

One or more stations in Earth Orbit
- Called ‘Satellites’

Uplink = transmission to satellite

Downlink = transmission to earth station

The satellite converts **uplink transmissions** into **downlink transmission** via a ‘**transponder**’.
Satellite Systems

Mobile User Link (MUL)

Inter Satellite Link (ISL)

Gateway Link (GWL)

footprint

PSTN: Public Switched Telephone Network

User data
Figure 10-4: Elements of a 12-channel (transponder) communications system.
Circulator: Ferrite material placed
Basics Advantages of Satellites

The advantages of satellite communication over terrestrial communication are:

- The coverage area of a satellite greatly exceeds that of a terrestrial system.
- Transmission cost of a satellite is independent of the distance from the center of the coverage area.
- Satellite to Satellite communication is very precise.
- Higher Bandwidths are available for use.
Basics Disadvantages of Satellites

The disadvantages of satellite communication:

- Launching satellites into orbit is costly.
- Satellite bandwidth is gradually becoming used up.
- There is a larger propagation delay in satellite communication than in terrestrial communication.
History
History

- Late 19th century, Marconi demonstrated feasibility of wireless communications.
- WWII
- 1st artificial satellite, SPUTNIK (1957)
- Reflecting Satellite, ECHO (1960)
- Store and Forward Satellite, COURIER (1960)
- Active Relay Satellite, TELSTAR (1962)
- 1st Geostationary Satellite, SYNCOM (1963)
- 1st Commercial Geostationary Satellite, INTELSAT-1 (1965)
Important Milestones (before 1950)

Putting the concepts together

- 1600 Tycho Brache’s experimental observations on planetary motion.
- 1609-1619 Kepler’s laws on planetary motion
- 1926 First liquid propellant rocket launched by R.H. Goddard in the US.
- 1927 First transatlantic radio link communication
- 1942 First successful launch of a V-2 rocket in Germany.
- 1945 Arthur Clarke publishes his ideas on geostationary satellites for worldwide communications (GEO concept).
V2 Rocket
Important Milestones (1950’s)

Putting the pieces together

- 1956 - Trans-Atlantic cable opened (about 12 telephone channels – operator).
- 1957 First man-made satellite launched by former USSR (Sputnik, LEO).
- 1958 First US satellite launched (SCORE). First voice communication established via satellite (LEO, lasted 35 days in orbit after batteries failed).
Sputnik - I
Explorer - I

http://www.youtube.com/watch?v=bHYyzLu1Gew
Important Milestones (1960’s)

First satellite communications

- 1960: First passive communication satellite launched into space (Large balloons, Echo I and II).
- 1962: First non-government active communication satellite launched Telstar I (MEO).
- 1963: First satellite launched into geostationary orbit Syncom 1 (comms. failed).
- 1965: First communications satellite launched into geostationary orbit for commercial use Early Bird (re-named INTELSAT 1).
ECHO I

http://www.youtube.com/watch?v=s8QC5sbKnF0
Telstar I

http://www.youtube.com/watch?v=3P5qHQX3oLE&feature=related
Intelsat I
Important Milestones (1970’s)
GEO applications development

- 1972 First domestic satellite system operational (Canada). INTERSPUTNIK founded.
- 1975 First successful direct broadcast experiment (one year duration; USA-India).
- 1977 A plan for direct-to-home satellite broadcasting assigned by the ITU in regions 1 and 3 (most of the world except the Americas).
- 1979 International Mobile Satellite Organization (Inmarsat) established.
Important Milestones (1980’s)
GEO applications expanded

- 1981 First reusable launch vehicle flight.
- 1982 International maritime communications made operational.
- 1983 ITU direct broadcast plan extended to region 2.
- 1984 First direct-to-home broadcast system operational (Japan).
- 1987 Successful trials of land-mobile communications (Inmarsat).
- 1989-90 Global mobile communication service extended to land mobile and aeronautical use (Inmarsat)
Important Milestones (1990’s)

1990-95:
- Several organizations propose the use of non-geostationary (NGSO) satellite systems for mobile communications.
- Continuing growth of VSATs around the world.
- Spectrum allocation for non-GEO systems.
- Continuing growth of direct broadcast systems. DirectTV created.

1997:
- Launch of first batch of LEO for hand-held terminals (Iridium).
- Voice service telephone-sized desktop and paging service pocket size mobile terminals launched (Inmarsat).

1998: Iridium initiates services.

1999: Globalstar Initiates Service.

2000: ICO initiates Service. Iridium fails and system is sold to Boeing.
Iridium

http://www.youtube.com/watch?v=dFBpsTC8y60
MEASAT

MEASAT-1+2 Boeing 376

http://www.youtube.com/watch?v=fdzfSX5hQgo&feature=related

MEASAT-3 Boeing 601

http://www.youtube.com/watch?v=PAHRJOVeJMU&feature=related
Satellite communication began after the Second World War when scientists knew that it was possible to build rockets that would carry radio transmitters into space.

1945  Arthur C. Clarke publishes an essay about “Extra Terrestrial Relays”
1957  first satellite SPUTNIK by Soviet Union during the cold war
1960  first reflecting communication satellite ECHO by US
1963  first geostationary satellite SYNCOM for news broadcasting
1965  first commercial geostationary satellite “Early Bird“ (INTELSAT I): 240 duplex telephone channels or 1 TV channel, 1.5 years lifetime
1976  three MARISAT satellites for maritime communication
1982  first mobile satellite telephone system INMARSAT-A
1988  first satellite system for mobile phones and data communication INMARSAT-C (data-rates about 600 bits/s)
1993  first digital satellite telephone system
1998  global satellite systems for small mobile phones
Overview and Basic concepts of Satellite Communications
Earth’s atmosphere

Source: All about GPS [www.kowoma.de]
Orbits:

- **GEO**: 36,000 km
- **MEO**: 5,000 – 15,000 km
- **LEO**: 160 - 2000 km
Orbits

- Orbit
  - Can be circular or elliptical around the center of earth
  - Can be in different (e.g. polar or equatorial) or same planes
  - Can be Geostationary (GEO), Medium (MEO) or Low (LEO)
  - Coverage is affected by objects such as buildings, by atmospheric attenuation, and electrical noise from earth
Three different types of satellite orbits can be identified depending on diameter of the orbit:

- **GEO (Geostationary Earth Orbit)**, 36000 km above earth surface
- **LEO (Low Earth Orbit)**: 160 - 2000 km
- **MEO (Medium Earth Orbit) or ICO (Intermediate Circular Orbit)**: 6000 - 20000 km
Orbits: GEO

- Geostationary Earth Orbit (GEO)
  - Proposed by Arthur C Clarke in 1945 and have been operational since 1960s
  - Same speed as Earth
    - Appears to stay still
    - 35,863km above the Earth above Equator
  - Common for early applications like Weather and military
Geostationary Satellites (cont)

- Orbit 35,786 km distance to earth surface, orbit in equatorial plane (inclination 0°)
  - complete rotation exactly one day, satellite is synchronous to earth rotation
- fix antenna positions, no adjusting necessary
- satellites typically have a large footprint (up to 34% of earth surface!), therefore difficult to reuse frequencies
- bad elevations in areas with latitude above 60° due to fixed position above the equator
- high transmit power needed
- high latency due to long distance
- not useful for global coverage for small mobile phones and data transmission, typically used for radio and TV transmission
Geostationary Satellites (cont)

• GEO
  – Advantages
    • Relative stationary property means frequency changes are not a problem
    • Tracking by Earth stations is simple
    • Can ‘see’ huge areas, so less satellites needed
  – Disadvantages
    • 35,000km is a long way for signals to travel
    • Polar regions not well served
    • Long delay (i.e. distance/Light Velocity)

Quiz: How much is the latency???
Geostationary Satellites (cont)

• Long delay… \((2 \times 35,863)/300000 = 0.24s\)
Quiz

• Satellite orbits are classified by their distance from Earth’s surface: LEO (160-2000KM), MEO (2000-20000km) & GEO (35786km). Find the round trip delay of data sent between a satellite and the earth for LEO, MEO and GEO satellite, assuming the speed of light is 300000000m/s. if the maximum acceptable delay for a voice system is 30ms, which of these satellite system would be acceptable for two-way voice communication?
**Satellite communications.** Satellite orbits are classified by their distance from the Earth’s surface: LEO (low earth orbit, 160–2000 km), MEO (medium earth orbit, 2000–20000 km), and GEO (geostationary earth orbit, 35786 km). Find the round-trip delay of data sent between a satellite and the earth for LEO, MEO, and GEO satellites, assuming the speed of light is $3 \times 10^8$ m/s. If the maximum acceptable delay for a voice system is 30ms, which of these satellite systems would be acceptable for two-way voice communication?

**SOLUTION (15 points)**

**LEO (low earth orbit):** 160–2000 km above the Earth’s surface:

\[
\frac{2 \cdot 160 \times 10^3}{3 \times 10^8} = 1.07 \text{ ms} \leq \text{round trip delay} \leq \frac{2 \cdot 2000 \times 10^3}{3 \times 10^8} = 13.3 \text{ ms}
\]

**MEO (medium earth orbit):** 2000–20000 km:

\[
\frac{2 \cdot 2000 \times 10^3}{3 \times 10^8} = 13.3 \text{ ms} \leq \text{round trip delay} \leq \frac{2 \cdot 20000 \times 10^3}{3 \times 10^8} = 133 \text{ ms}
\]

**GEO (geostationary earth orbit):** 35786 km:

\[
\text{round trip delay} \geq \frac{2 \cdot 35786 \times 10^3}{3 \times 10^8} = 239 \text{ ms}
\]

Only LEO satellites and MEO satellites below 4500 km have delay less than 30 ms.
Orbits: LEO

- Low Earth Orbit (LEO)
  - Circular or Elliptical orbit, under 2000km
  - Often in polar orbit at 500 to 1500 km altitude
  - Appear to move, usually 1.5 to 2 hours to orbit once
  - Coverage diameter about 8000km
  - Delay low, about 20ms
  - Only visible to Earth stations for about 20 minutes
  - Frequencies change with movement (Doppler shifts)
Low Earth Orbit (cont)

- Requires many satellites in many planes for global coverage
- Small foot-print, better frequency reuse
- Satellites must communicate with each other to hand-over signals
- More complex system
- Cheaper kit with better signal strength, and bandwidth efficiency
- Used in mobile communications systems, with increased use in 3G systems
**Orbits: MEO**

- Medium Earth Orbit (MEO)
  - Altitude 6000 to 20000km
  - 6 hour orbits
  - Coverage diameter 10000 to 15000km
  - Signal delay <80ms
  - Visible for a ‘few’ hours
  - Proposed for data communication services
**MEO systems**

- comparison with LEO systems:
  - slower moving satellites
  - less satellites needed
  - simpler system design
  - for many connections no hand-over needed
  - higher latency, i.e. 70 - 80 ms
  - higher sending power needed
  - special antennas for small footprints needed
MOLNIYA VIEW OF THE EARTH
(Apogee remains over the northern hemisphere)

http://www.youtube.com/watch?v=jlNEHKpQyio&feature=related
Molniya Variants

• Tundra Orbit – Lies entirely above the Van Allen belts.

• The Russian Tundra system, which employs two satellites in two 24-hour orbits separated by 180 deg around the Earth, with an apogee of 53,622 km and a perigee of 17,951 km.

• The Molniya orbit crosses the Van Allen belts twice for each revolution, resulting in a reduction of satellite life due to impact on electronics.

• the Russian Molniya system employs three satellites in three 12-hour orbits separated by 120 deg around the Earth, with an apogee of 39,354 km and a perigee of 1000 km.
Molniya Variants (HEO’s)

• The LOOPUS orbit. The LOOPUS system employs three satellites in three eight-hour orbits separated by 120 deg around the Earth, with an apogee of 39,117 km and a perigee of 1238 km.

• The ELLIPSO orbit
Summary:

- GEOSTATIONARY ORBIT
- In the equatorial plane
- Orbital Period = 23 h 56 min. 4.091 s = one Sidereal Day (defined as one complete rotation relative to the fixed stars)
- Satellite appears to be stationary over a point on the equator to an observer
- Radius of orbit, $r$, = 42,164.57 km

NOTE: Radius = orbital height + radius of the earth
Average radius of earth = 6,378.14 km
Summary:

• Low Earth Orbit (>250 km); T ≈ 92 minutes
• Polar (Low Earth) Orbit; earth rotates about 23° each orbit; useful for surveillance
• Sun Synchronous Orbit (example, Tiros-N/NOAA satellites used for search and rescue operations)
• 8-hour and 12-hour orbits
• Molniya orbit (Highly Elliptical Orbit (HEO); T ≈ 11h 38 min; highly eccentric orbit; inclination 63.4 degrees
MOLNYA Orbit 1/2

- Period = 11h 58m 2s
- Inclination = 63.4°
- Eccentricity = 0.6 to 0.75
- Apogee altitude = 39105 km
- Perigee altitude = 1250 km
- Visibility duration > 8 h

See [2], Section 2.2.1.1 'MOLNYA' orbits, pp. 51-53.
See http://en.wikipedia.org/wiki/Molniya_orbit
See [2], Section 2.2.1.1 'MOLNYA' orbits, pp. 51-53.
See http://en.wikipedia.org/wiki/Molniya_orbit
TUNDRA Orbit 1/2

- Period = 23h 56m 4s
- Inclination = 63.4°
- Eccentricity = 0.25 to 0.4
- Apogee altitude = 46340 km
- Perigee altitude = 25231 km
- Visibility duration > 12 h

See [2], Section 2.2.1.1 ‘TUNDRA’ orbits, pp. 53-56.
See http://en.wikipedia.org/wiki/Tundra_orbit
TUNDRA Orbit

Adopted from [2], Fig. 2.13, pp. 54.

See [2], Section 2.2.1.1 ‘TUNDRA' orbits, pp. 53-56.
See http://en.wikipedia.org/wiki/Tundra_orbit
## Parameters Determining Orbit Size and Shape

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Semimajor Axis</strong></td>
<td>Half the distance between the two points in the orbit that are farthest apart</td>
</tr>
<tr>
<td><strong>Apogee/Perigee Radius</strong></td>
<td>Measured from the center of the Earth to the points of maximum and minimum radius in the orbit</td>
</tr>
<tr>
<td><strong>Apogee/Perigee Altitude</strong></td>
<td>Measured from the &quot;surface&quot; of the Earth (a theoretical sphere with a radius equal to the equatorial radius of the Earth) to the points of maximum and minimum radius in the orbit</td>
</tr>
<tr>
<td><strong>Period</strong></td>
<td>The duration of one orbit, based on assumed two-body motion</td>
</tr>
<tr>
<td><strong>Mean Motion</strong></td>
<td>The number of orbits per solar day (86,400 sec/24 hour), based on assumed two-body motion</td>
</tr>
<tr>
<td><strong>Eccentricity</strong></td>
<td>The shape of the ellipse comprising the orbit, ranging between a perfect circle (eccentricity = 0) and a parabola (eccentricity = 1)</td>
</tr>
</tbody>
</table>
\[ c = \text{distance from center of Earth to center of ellipse} = \text{eccentricity} \times \text{semimajor axis} \]
## Orientation of Orbital Plane in Space

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inclination</strong></td>
<td>The angle between the orbital plane and the Earth's equatorial plane (commonly used as a reference plane for Earth satellites)</td>
</tr>
<tr>
<td><strong>Right Ascension of the Ascending Node</strong></td>
<td>The angle in the Earth's equatorial plane measured eastward from the vernal equinox to the ascending node of the orbit</td>
</tr>
<tr>
<td><strong>Argument of Perigee</strong></td>
<td>The angle, in the plane of the satellite's orbit, between the ascending node and the perigee of the orbit, measured in the direction of the satellite's motion</td>
</tr>
<tr>
<td><strong>Longitude of the Ascending Node</strong></td>
<td>The Earth-fixed longitude of the ascending node</td>
</tr>
</tbody>
</table>

The ascending node (referenced in three of the above definitions) is the point in the satellite's orbit where it crosses the Earth's equatorial plane going from south to north.
Parameters determining orbit orientation

Orbit Geometry

Legend:
- $\Omega$ = right ascension of ascending node
- $\omega$ = argument of perigee, periapsis
- $i$ = inclination
- $\theta$ = true anomaly
LOCATING THE SATELLITE - 1

Find the **Ascending Node**

Point where the satellite crosses the equatorial plane from South to North

- Inclination
- Right Ascension of the Ascending Node (= RA from Fig. 2.6 in text)

See next slide
Fig. 2.9 in text

- Center of earth
- Argument of Perigee
- Right Ascension
- First Point of Aries
- Orbit passes through equatorial plane here
- Inclination of orbit
- Equatorial plane
DEFINING PARAMETERS 2

(Source: M. Richaria, Satellite Communication Systems, Fig. 2.9)
LOCATING THE SATELLITE - 2

\[ \Omega \text{ and } i \text{ together locate the Orbital plane with respect to the Equatorial plane.} \]

\[ \omega \text{ locates the Orbital coordinate system with respect to the Equatorial coordinate system.} \]
Satellite Location parameters

To specify the satellite's location within its orbit at epoch.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>True Anomaly</td>
<td>The angle from the eccentricity vector (points toward perigee) to the satellite position vector, measured in the direction of satellite motion and in the orbit plane.</td>
</tr>
<tr>
<td>Mean Anomaly</td>
<td>The angle from the eccentricity vector to a position vector where the satellite would be if it were always moving at its angular rate.</td>
</tr>
<tr>
<td>Eccentric Anomaly</td>
<td>An angle measured with an origin at the center of an ellipse from the direction of perigee to a point on a circumscribing circle from which a line perpendicular to the semimajor axis intersects the position of the satellite on the ellipse.</td>
</tr>
<tr>
<td>Argument of Latitude</td>
<td>The sum of the True Anomaly and the Argument of Perigee.</td>
</tr>
<tr>
<td>Time Past Ascending Node</td>
<td>The elapsed time since the last ascending node crossing.</td>
</tr>
<tr>
<td>Time Past Perigee</td>
<td>The elapsed time since last perigee passage.</td>
</tr>
</tbody>
</table>
LOCATING THE SATELLITE IN ORBIT: 2

- Need to develop a procedure that will allow the average angular velocity to be used.
- If the orbit is not circular, the procedure is to use a **Circumscribed Circle**.
- A circumscribed circle is a circle that has a radius equal to the semi-major axis length of the ellipse and also has the same center.

See next slide
**ORBIT ECCENTRICITY**

- If $a =$ semi-major axis,
  $b =$ semi-minor axis, and
  $e =$ eccentricity of the orbit ellipse,

then

$$e = \frac{a - b}{a + b}$$

**NOTE:** For a circular orbit, $a = b$ and $e = 0$
• Orbital Mechanics
## Orbital Velocities and Periods

<table>
<thead>
<tr>
<th>Satellite System</th>
<th>Orbital Height (km)</th>
<th>Orbital Velocity (km/s)</th>
<th>Orbital Period h min s</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTELSAT</td>
<td>35,786.43</td>
<td>3.0747</td>
<td>23 56 4.091</td>
</tr>
<tr>
<td>ICO-Global</td>
<td>10,255</td>
<td>4.8954</td>
<td>5 55 48.4</td>
</tr>
<tr>
<td>Skybridge</td>
<td>1,469</td>
<td>7.1272</td>
<td>1 55 17.8</td>
</tr>
<tr>
<td>Iridium</td>
<td>780</td>
<td>7.4624</td>
<td>1 40 27.0</td>
</tr>
</tbody>
</table>
Reference Coordinate Axes 1: Earth Centric Coordinate System

The earth is at the center of the coordinate system.
Reference planes coincide with the equator and the polar axis.

More usual to use this coordinate system.
Reference Coordinate Axes 2: Satellite Coordinate System

The earth is at the center of the coordinate system and reference is the plane of the satellite’s orbit
The Forces

Inward Force \( \vec{F} \)

\[
\vec{F} = -\frac{GM_Em\vec{r}}{r^3}
\]

Equation (2.7)

\( G = \) Gravitational constant = \( 6.672 \times 10^{-11} \) Nm\(^2\)/kg\(^2\)

\( M_E = \) Mass of the earth (and \( GM_E = \mu = \) Kepler’s constant)

\( m = \) mass of satellite

\( r = \) satellite orbit radius from center of earth

\( \vec{r} = \) unit vector in the \( r \) direction (positive \( r \) is away from earth)
KEPLER’S THREE LAWS

- Orbit is an ellipse (a smooth closed curve which is symmetric about its horizontal and vertical axes) with the larger body (earth) at one focus.
- The satellite sweeps out equal arcs (area) in equal time (**NOTE**: for an ellipse, this means that the orbital velocity varies around the orbit)
- The square of the period of revolution equals a CONSTANT \( \times \) the THIRD POWER of SEMI-MAJOR AXIS of the ellipse

We’ll look at each of these in turn
Review: Ellipse analysis

- Points (-c,0) and (c,0) are the **foci**.
- Points (-a,0) and (a,0) are the **vertices**.
- Line between vertices is the **major axis**.
- \( a \) is the length of the **semimajor axis**.
- Line between (0,b) and (0,-b) is the **minor axis**.
- \( b \) is the length of the **semiminor axis**.

The vertices are at \((\pm a, 0)\), and the foci at \((\pm c, 0)\). The foci are always located on the major axis.

The length of the major axis is 2a; the length of the minor axis is 2b.

If the ellipse has a vertical major axis: then the constant under \( y^2 \) is larger than the constant under \( x^2 \).

\[
a^2 = b^2 + c^2
\]

Standard Equation:

\[
\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1
\]

Area of ellipse:

\[
A = \pi ab
\]
KEPLER 1: Elliptical Orbits

Figure 2.6 in text

Law 1

The orbit is an ellipse

e = ellipse’s eccentricity
O = center of the earth (one focus of the ellipse)
C = center of the ellipse
a = (Apogee + Perigee)/2
Equation 2.17 in text:
(describes a conic section, which is an ellipse if $e < 1$)

$$r_0 = \frac{p}{1 + e \cos(\phi_0)}$$

$e = \text{eccentricity}$

$e < 1 \implies \text{ellipse}$

$e = 0 \implies \text{circle}$

$r_0 = \text{distance of a point in the orbit to the center of the earth}$

$p = \text{geometrical constant (width of the conic section at the focus)}$

$p = a(1-e^2)$

$\phi_0 = \text{angle between } r_0 \text{ and the perigee}$

Eccentricity, $e$, indicates how an ellipse deviates from the shape of a circle:

$e = c/a$

A perfect circle has an eccentricity of zero, while more and more elongated ellipses have higher eccentricities $\leq 1$.  

$[0 \leq e \leq 1]$
LOCATING THE SATELLITE IN ORBIT: 1

Start with Fig. 2.6 in Text

φ₀ is the *True Anomaly*
See eq. (2.22)

*C* is the center of the orbit ellipse
*O* is the center of the earth

NOTE: *Perigee* and *Apogee* are on opposite sides of the orbit
**KEPLER 2: Equal Arc-Sweeps**

**Law 2**

If \( t_2 - t_1 = t_4 - t_3 \)

then \( A_{12} = A_{34} \)

Velocity of satellite is *SLOWEST* at *APOGEE*; *FASTEST* at *PERIGEE*
KEPLER 3: Orbital Period

Orbital period and the Ellipse are related by

\[ T^2 = \left( 4 \pi^2 a^3 \right) / \mu \]  

(Equation 2.21)

\[ \mu = \text{Kepler’s Constant} = GM_E \]

That is the \textbf{square} of the period of revolution is equal to a \textbf{constant} \times \textbf{cube} of the semi-major axis.
**Solar vs. Sidereal Day**

- **A sidereal day** is the time between consecutive crossings of any particular longitude on the earth by any star other than the sun. *The sidereal day is the time the Earth takes to rotate 360 degrees, that is in relation to the stars. It is 23 hours 56 minutes 4.09 seconds in length when one compares it with mean solar day which is 24 hours in length. [The Earth rotates 360.98 degrees in 24 hours.]*

- **A solar day** is the time between consecutive crossings of any particular longitude of the earth by the sun-earth axis.
  - Solar day = EXACTLY 24 hrs
  - Sidereal day = 23 h 56 min. 4.091 s

http://www.youtube.com/watch?v=lwVf-AvD8ds
Why the difference?

By the time the Earth completes a full rotation with respect to an external point (not the sun), it has already moved its center position with respect to the sun. The extra time it takes to cross the sun-earth axis, averaged over 4 full years (because every 4 years one has 366 days) is of about 3.93 minutes per day.

Calculation next page
Solar vs. Sidereal Day

Numerical Calculation:

4 years = 1461 solar days (365*4 +1)
4 years : earth moves 1440 degrees (4*360) around sun.
1 solar day: earth moves 0.98 degrees (=1440/1461) around sun
1 solar day : earth moves 360.98 degrees around itself (360 + 0.98)
1 sidereal day = earth moves 360 degrees around itself
1 solar day = 24hrs = 1440 minutes
1 sidereal day = 1436.7 minutes (1440*360/360.98)

Difference = **3.93 minutes**

(Source: M.Richaria, Satellite Communication Systems, Fig.2.7)
Quiz

Calculate the radius of a Geostationary Satellite, which must have orbital period of one Sidereal day?
**Answer**

- Period = 23h 56m 4.09s = 86164.09s

- $a^3 = (86164.09)^2 \times (3.986 \times 10^{14})/4\pi^2$

- $a = 42164$ km

- Altitude, $h = 42164 - 6378 = 35786$ km
The Geostationary Orbit:

Sidereal Day = 23 hrs 56 min 4.1 sec

Calculate radius and height of GEO orbit:

- \( T^2 = \frac{4 \pi^2 a^3}{\mu} \) (eq. 2.21)
- Rearrange to \( a^3 = \frac{T^2 \mu}{4 \pi^2} \)
- \( T = 86,164.1 \) sec
- \( a^3 = (86,164.1)^2 \times 3.986004418 \times 10^5 / (4 \pi^2) \)
- \( a = 42,164.172 \) km = orbit radius
- \( h = \) orbit radius – earth radius = 42,164.172 – 6378.14
  = 35,786.03 km
Quiz:

Space Shuttle Circular orbit (height = \( h = 250 \) km). Use earth radius = 6378 km

a. Period = ?

b. Linear velocity = ?

Solution:
Quiz:

Space Shuttle Circular orbit (height = h = 250 km). Use earth radius = 6378 km

a. Period = ?

b. Linear velocity = ?

Solution:

a) \[ r = (r_e + h) = 6378 + 250 = 6628 \text{ km} \]

From equation 2.21:

\[ T^2 = \frac{(4 \pi^2 a^3)}{\mu} = \frac{4 \pi^2 \times (6628)^3}{3.986004418 \times 10^5} \text{ s}^2 \]

\[ T = 5370.13 \text{ s} = 89 \text{ mins 30.13 secs} \]

b) The circumference of the orbit is \[ 2\pi a = 41,644.95 \text{ km} \]

\[ v = \frac{2\pi a}{T} = \frac{41,644.95}{5370.13} = 7.755 \text{ km/s} \]

Alternatively:

\[ v = \left(\frac{\mu}{r}\right)^2 = 7.755 \text{ km/s}. \]
Quiz:

Elliptical Orbit: Perigee = 1,000 km, Apogee = 4,000 km

a. Period = ?
b. Eccentricity = ?

Solution:
Coordinate System 1

- **Latitude**: Angular distance, measured in degrees, north or south of the equator.
  - $\ell$ from -90 to +90 (or from 90S to 90N)
- **Longitude**: Angular distance, measured in degrees, from a given reference longitudinal line (Greenwich, London).

Quiz: What is the longitude and latitude of KyuTech?
Latitude ($\theta^\circ N$) and longitude ($\phi^\circ E$) of a point A.

(Source: M.Richaria, Satellite Communication Systems, Fig.2.9)
LOOK ANGLES 1

- **Azimuth**: Measured eastward (clockwise) from geographic north to the projection of the satellite path on a (locally) horizontal plane at the earth station.

- **Elevation Angle**: Measured upward from the local horizontal plane at the earth station to the satellite path.
Coverage vs. Altitude
Minimum Delay for two hops
Spectrum Allocation
SATCOM Frequencies Usage

Commercial SATCOM Services

ALL CAPS = Fixed Satellite Service (FSS)
small case = Mobile Satellite Service (MSS)/Personal Comm Services (PCS)

"regular" cellular (Land Mobile Radio)
inmarsat, odyssey, indium, globalstar
inmarsat, odyssey, indium, globalstar

INTELSAT, inmarsat, odyssey

TELEDESIC, COMMERCIAL, odyssey, indium, gateway links
SPACEWAY, CYBERSTAR, ASTROLINK TELEDIESIC
indium, odyssey (gateway links)

3 GHz

30 GHz

S

C

X

Ku

K

Ka

V

Military UHF Band

Government S-Band (SGLS)

Military EHF (44/20)

Government / Military SATCOM Services

Freq at Risk: Int’l & US Commercial encroachment

Heavy orbital/terrestrial congestion: much coordination with terrestrial users needed

SATCOM users are secondary in UHF: subject to interference from terrestrial users
Frequency Spectrum concepts:

• Frequency: Rate at which an electromagnetic wave reverts its polarity (oscillates) in cycles per second or **Hertz** (Hz).

• Wavelength: distance between wavefronts in space. Given in meters as: \( \lambda = \frac{c}{f} \)

  Where: \( c = \text{speed of light} \ (3 \times 10^8 \text{ m/s in vacuum}) \)
  \[ f = \text{frequency in Hertz} \]

• Frequency band: range of frequencies.

• Bandwidth: Size or “width” (in Hertz) or a frequency band.

• Electromagnetic Spectrum: full extent of all frequencies from zero to infinity.
Radio Frequencies (RF)

RF Frequencies: Part of the electromagnetic spectrum ranging between 300 MHz and 300 GHz. Interesting properties:

- Efficient generation of signal power
- Radiates into free space
- Efficient reception at a different point.

Differences depending on the RF frequency used:

- Signal Bandwidth
- Propagation effects (diffraction, noise, fading)
- Antenna Sizes
Microwave Frequencies

- Sub-range of the RF frequencies approximately from 1GHz to 30GHz. Main properties:
  - Line of sight propagation (space and atmosphere).
  - Blockage by dense media (hills, buildings, rain)
  - Wide bandwidths compared to lower frequency bands.
  - Compact antennas, directionality possible.
  - Reduced efficiency of power amplification as frequency grows:

  Radio Frequency Power OUT
  Direct Current Power IN
Spectrum Regulation

International Telecommunication Union (ITU): Members from practically all countries around the world.

- Allocates frequency bands for different purposes and distribute them around the planet.

- Creates rules to limit RF Interference (RFI) between countries that reuse same RF bands.

- Mediates disputes and creates rules to deal with harmful interference when it occurs.

- Meets bi-annually with its members, to review rules and allocations: World Radio Communication Conference (WRC).

- There are also the Regional Radio Communication Conferences (RCC), which happen less often.
Radio Frequency Spectrum
Commonly Used Bands

Terrestrial Bands
Space Bands
Shared (Terrestrial and Space)
Space-Earth Frequency Usability

Atmospheric attenuation effects for Space-to-Earth as a function of frequency (clear air conditions).

(a) Oxygen; (b) Water vapor. [Source: ITU © 1988]

Resonance frequencies below 100GHz:

- 22.2GHz (H$_2$O)
- 53.5-65.2 GHz (Oxygen)
LEO satellites need lower RF frequencies:

- Omni-directional antennas have low gain - typically $G = 0 \text{ db} = 1$
- Flux density $F$ in $W/m^2$ at the earth’s surface in any beam is independent of frequency
- Received power is $F \times A$ watts, where $A$ is effective area of antenna in square meters
- For an omni-directional antenna $A = G \frac{\lambda^2}{4\pi} = \frac{\lambda^2}{4\pi}$
- At $450 \text{ MHz}$, $A = 353 \text{ cm}^2$, at $20 \text{ GHz}$, $A = 0.18 \text{ cm}^2$
Insights on Frequency Selection:
(Part 2: Higher frequencies, higher capacity)

- GEO satellites need more RF frequencies
  - High speed data links on GEO satellites need about 0.8 Hz of RF bandwidth per bit/sec.
  - A 155 Mbps data link requires 125 MHz bandwidth
Satellite Network Configurations
Categorisation

- **Coverage area**: global, regional or national. Larger systems require more satellites

- **Service type**: fixed satellite service (FSS), broadcast satellite service (BSS), or mobile satellite service (MSS)
Satellite Network Configurations

- **Point to Point**
  - Two earth stations and one satellite

- **Broadcast Link**
  - One earth transmitter, one satellite, many receivers
VSAT (Very Small Aperture Terminal)

- Two-way communications via ground hub
- Subscribers have low cost antennas
- Subscribers communicate via hub
Link Problems of Satellites

- Propagation delay
- Propagation loss of signals depends on distance, angle and atmospheric condition
  - Parameters like attenuation or received power determined by four parameters:
    - sending power
    - gain of sending antenna
    - distance between sender and receiver
    - gain of receiving antenna
- Varying strength of received signal due to multipath propagation
- Interruptions due to shadowing of signal (no LOS)

Possible solutions
- Satellite diversity (usage of several visible satellites at the same time) helps to use less sending power
System Elements
Satellite Subsystems

- Communications
  - Antennas
  - Transponders

- Common Subsystem (Bus Subsystem)
  - Telemetry/Command (TT&C)
  - Satellite Control (antenna pointing, attitude)
  - Propulsion
  - Electrical Power
  - Structure
  - Thermal Control
Ground Segment
Collection of facilities, users and applications.

Earth Station = Satellite Communication Station (air, ground or sea, fixed or mobile).
System Design Considerations
Basic Principles

![Diagram of satellite communication system]

- **Uplink**
- **Downlink**
- **Source Information**
- **Output Information**

**Satellite**

**Earth Station**

**Tx**

**Rx**
Satellite Communications

Design considerations

- Area/coverage; some satellites can cover almost 33% of earth's surface, transmission cost becomes invariant of distance
- Bandwidth; is a very limited resource.
- Transmission quality; is usually very high, though delay can be up to ¼ second

Frequency bands:

- C-band (4 and 6 GHz)
- Ku-band (11 and 14 GHz)
- Ka-band (19 and 29 GHz)
Separating Signals

Up and Down:

- **FDD**: Frequency Division Duplexing.
  - $f_1 = \text{Uplink}$
  - $f_2 = \text{Downlink}$

- **TDD**: Time Division Duplexing.
  - $t_1 = \text{Up}$, $t_2 = \text{Down}$, $t_3 = \text{Up}$, $t_4 = \text{Down}$, ...

- **Polarization**
  - V & H linear polarization
  - RH & LH circular polarizations
Separating Signals
(so that many transmitters can use the same transponder simultaneously)

📊 Between Users or “Channels” (Multiple Access):

- **FDMA:** Frequency Division Multiple Access; assigns each transmitter its own carrier frequency
  
  \[
  f_1 = \text{User 1}; \ f_2 = \text{User 2}; \ f_3 = \text{User 3}, \ldots
  \]

- **TDMA:** Time Division Multiple Access; each transmitter is given its own time slot
  
  \[
  t_1 = \text{User}_1, \ t_2 = \text{User}_2, \ t_3 = \text{User}_3, \ t_4 = \text{User}_1, \ldots
  \]

- **CDMA:** Code Division Multiple Access; each transmitter transmits simultaneously and at the same frequency and each transmission is modulated by its own pseudo randomly coded bit stream
  
  Code 1 = User 1; Code 2 = User 2; Code 3 = User 3
Digital Communication System

TRANSMITTER

Source Data → Source Coding → Channel Coding → Modulator

RECEIVER

Output Data → Source Decoding → Channel Decoder → Demodulator

RF Channel
Satellite Systems Applications
<table>
<thead>
<tr>
<th>Year</th>
<th>Satellite</th>
<th>Mass</th>
<th>Circuits/Power/Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>Early Bird</td>
<td>34 kg</td>
<td>240 telephone circuits</td>
</tr>
<tr>
<td>1968</td>
<td>Intelsat III</td>
<td>152 kg</td>
<td>1500 circuits</td>
</tr>
<tr>
<td>1986</td>
<td>Intelsat VI</td>
<td>1,800 kg</td>
<td>33,000 circuits</td>
</tr>
<tr>
<td>2000</td>
<td>Large GEO</td>
<td>3000 kg</td>
<td>8 - 15 kW power, 1,200 kg payload</td>
</tr>
</tbody>
</table>
Current GEO Satellite Applications:

- Broadcasting - mainly TV at present
  - DirecTV, PrimeStar, etc.

- Point to Multi-point communications
  - VSAT, Video distribution for Cable TV

- Mobile Services
  - Motient (former American Mobile Satellite), INMARSAT, etc.
Several new systems are just starting service

- Circular or inclined orbit with < 1400 km altitude
- Satellite travels across sky from horizon to horizon in 5 - 15 minutes
- Earth stations must track satellite or have omni-directional antennas
- Constellation of satellites is needed for continuous communication.
- Handoff needed.
Satellite Application Types

- Broadcast and Multicast of Digital Content
- Voice and Telephony Networks
- Data Communications and the Internet
- Mobile and Personal Communications