كلية الهندسة بشبرا

Shoubra faculty
of Engineering

4th year Communication

BENHA UNIVERSITY

Advanced Electronic Systems

Part 2

Lecture 2

- Satellite System Link Equations
- Satellite Application: Global Positioning System

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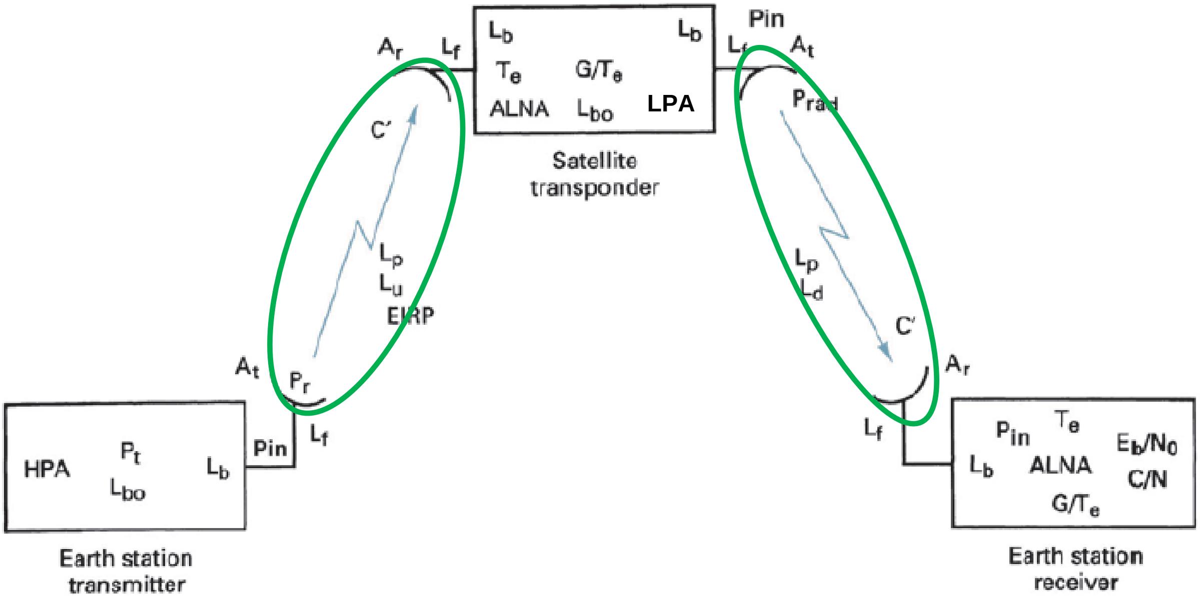
Satellite System Link Equations

- When evaluating the performance of a digital satellite system, the uplink and downlink parameters are first considered separately, then the overall performance is determined by combining them in the appropriate manner.



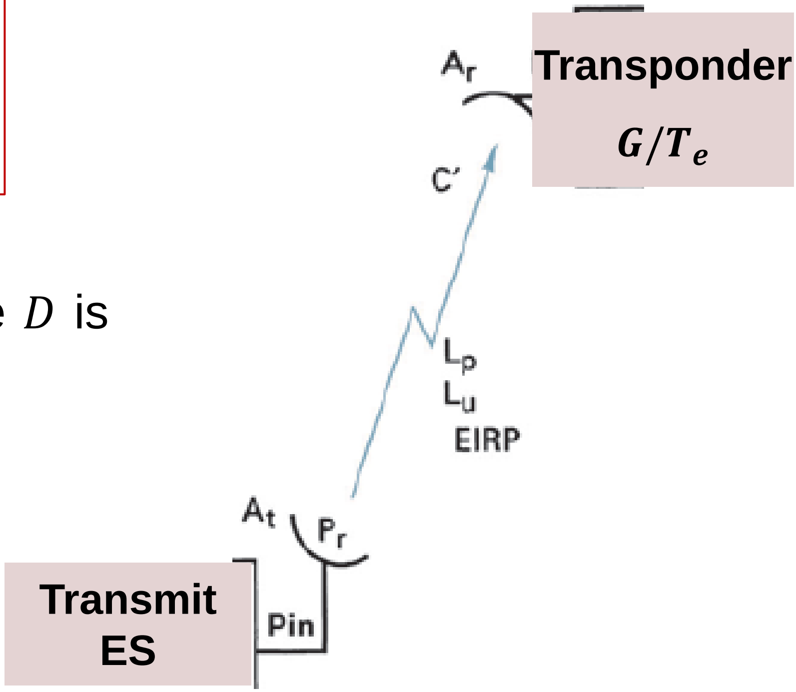
- The following link equations are used to separately analyze the uplink and downlink sections of a single radio-frequency carrier satellite system. These equations consider only the ideal gains and losses and effects of thermal noise associated with the ES transmitter, ES receiver, and the satellite transponder.

Uplink Equation

$$\frac{C}{\boldsymbol{N_0}} = \frac{P_{\mathrm{in}} A_{\mathrm{t}} \boxed{A_{\mathrm{r}}}}{L_{\mathrm{p}} L_{\mathrm{u}} \boldsymbol{K} \boxed{\boldsymbol{T_e}}} = \frac{P_{\mathrm{in}} A_{\mathrm{t}}}{L_{\mathrm{p}} L_{\mathrm{u}} K} \times \boxed{\frac{G}{T_e}}$$

$L_{\mathrm{p}} = (\frac{4\pi D}{\lambda})^2$ is the free space path loss where D is the propagation distance and λ is the wavelength.

L_{u} : additional uplink atmospheric losses



Transponder

G/T_e

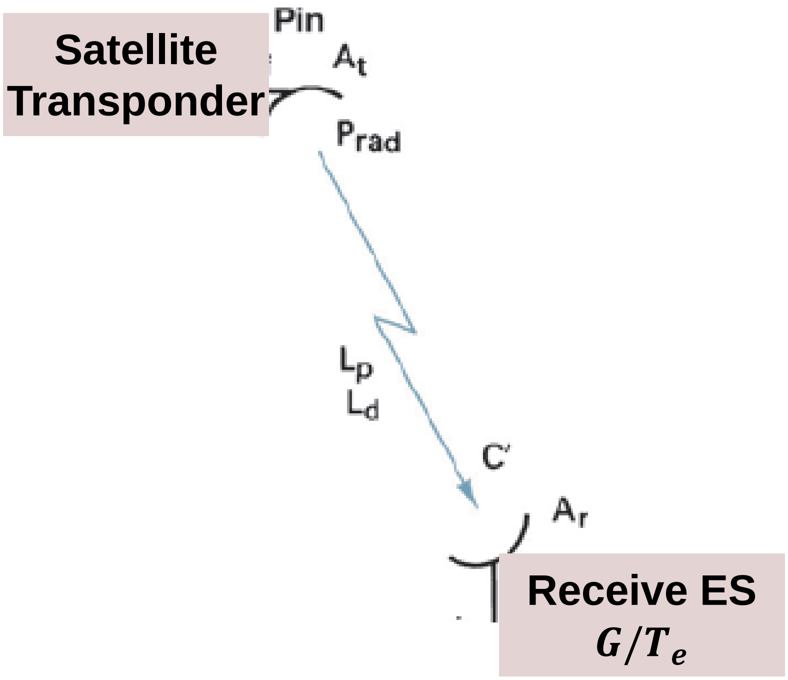
Transmit ES

Expressed in dB

$$\frac{C}{N_0}\,(\mathrm{dB}) = \underbrace{\mathrm{EIRP}\,(\mathrm{dBW})}_{\text{EIRP of Transmit ES}} - L_{\mathrm{p}}(\mathrm{dB}) - L_{\mathrm{u}}(\mathrm{dB}) + \underbrace{\frac{G}{T_e}\,(\mathrm{dBK}^{-1})}_{\text{Satellite transponder } G/T_e} - K(\mathrm{dBWK})$$

Downlink Equation

$$\frac{C}{\boldsymbol{N_0}} = \frac{P_{\mathrm{in}} A_{\mathrm{t}} A_{\mathrm{r}}}{L_{\mathrm{p}} L_{\mathrm{d}} \boldsymbol{K T_e}} = \frac{P_{\mathrm{in}} A_{\mathrm{t}}}{L_{\mathrm{p}} L_{\mathrm{d}} K} \times \frac{G}{T_e}$$


Satellite Transponder

Receive ES
$\boldsymbol{G/T_e}$

L_{d} : additional downlink atmospheric losses

Expressed in dB

$$\frac{C}{N_0}\,(\mathrm{dB}) = \underbrace{\mathrm{EIRP}\,(\mathrm{dBW})}_{\textbf{Satellite transponder EIRP}} - L_{\mathrm{p}}(\mathrm{dB}) - L_{\mathrm{d}}(\mathrm{dB}) + \underbrace{\frac{G}{T_e}\,(\mathrm{dBK}^{-1})}_{\boldsymbol{G/T_e}\textbf{ for Receive ES}} - K(\mathrm{dBWK})$$

Example: Calculate C/N_0 for the downlink with the following parameters

Satellite transmitter power	10 dBW
Satellite back-off loss	0.1 dB
Satellite branching and feeder loss	0.5 dB
Satellite transmit antenna gain	30.8 dB
Additional downlink atmospheric loss	0.4 dB
Free space path loss	205.6 dB
ES G/T_e ratio	37.7 dBK^{-1}

Answer:

$$\mathrm{EIRP}_{(\mathrm{dBW})} = P_{\mathrm{t(dBW)}} - L_{\mathrm{bo(dB)}} - L_{\mathrm{fb(dB)}} + A_{\mathrm{t(dB)}}$$

$$= 10\ \mathrm{dBW} - 0.1\ \mathrm{dB} - 0.5\ \mathrm{dB} + 30.8\ \mathrm{dB} = 40.2\ \mathrm{dBW}$$

$$\frac{C}{N_0}\ (\mathrm{dB}) = \mathrm{EIRP}\ (\mathrm{dBW}) - L_{\mathrm{p}}(\mathrm{dB}) - L_{\mathrm{d}}(\mathrm{dB}) + \frac{G}{T_e}\ (\mathrm{dBK}^{-1}) - K(\mathrm{dBWK})$$

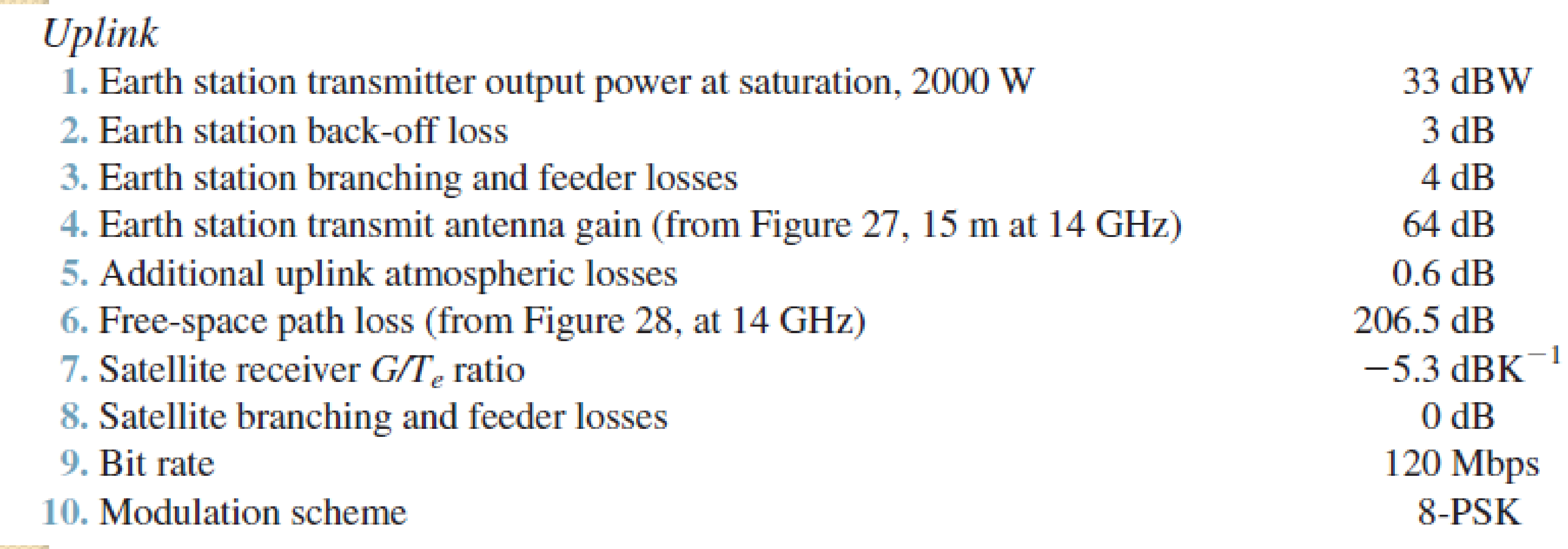
$$= 40.2\ \mathrm{dBW} - 205.6\ \mathrm{dB} - 0.4\ \mathrm{dB} + 37.7\ \mathrm{dBK}^{-1} - 10\log(1.38 \times 10^{-23})$$

$$= 100.5\ \mathrm{dB}$$

Link budget

- A link budget identifies the system parameters and is used to determine the projected C/N and Eb/N0 ratios at both the satellite and ES receivers for a given modulation scheme.

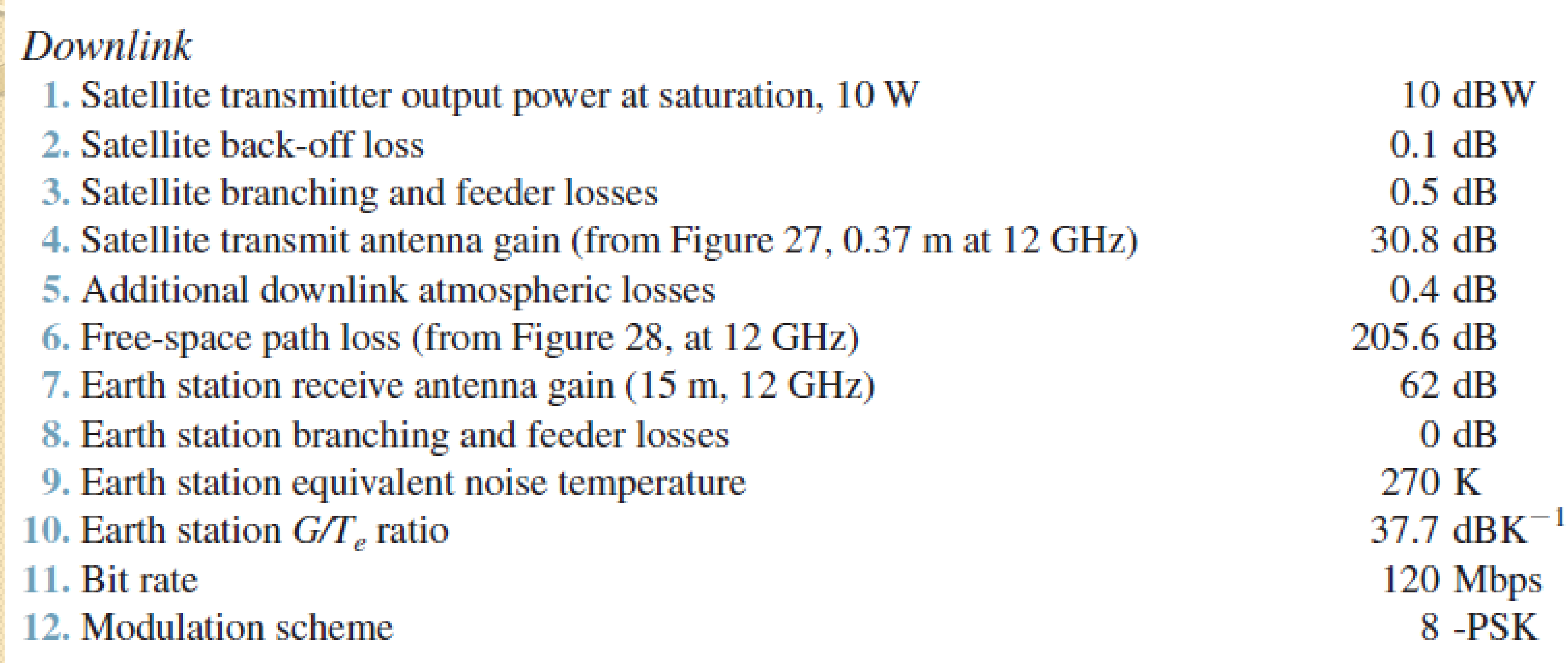
Example: Complete the link budget for satellite system with the following parameters



Uplink

1. Earth station transmitter output power at saturation, 2000 W	33 dBW
2. Earth station back-off loss	3 dB
3. Earth station branching and feeder losses	4 dB
4. Earth station transmit antenna gain (from Figure 27, 15 m at 14 GHz)	64 dB
5. Additional uplink atmospheric losses	0.6 dB
6. Free-space path loss (from Figure 28, at 14 GHz)	206.5 dB
7. Satellite receiver G/T_e ratio	-5.3 dBK^{-1}
8. Satellite branching and feeder losses	0 dB
9. Bit rate	120 Mbps
10. Modulation scheme	8-PSK

Link budget (cont'd)



Downlink

1.	Satellite transmitter output power at saturation, 10 W	10 dBW
2.	Satellite back-off loss	0.1 dB
3.	Satellite branching and feeder losses	0.5 dB
4.	Satellite transmit antenna gain (from Figure 27, 0.37 m at 12 GHz)	30.8 dB
5.	Additional downlink atmospheric losses	0.4 dB
6.	Free-space path loss (from Figure 28, at 12 GHz)	205.6 dB
7.	Earth station receive antenna gain (15 m, 12 GHz)	62 dB
8.	Earth station branching and feeder losses	0 dB
9.	Earth station equivalent noise temperature	270 K
10.	Earth station G/T_e ratio	37.7 dBK^{-1}
11.	Bit rate	120 Mbps
12.	Modulation scheme	8 -PSK

Solution

1) uplink budget (expressed as log)

$$\text{EIRP (earth station)} = P_t + A_t - L_{\text{bo}} - L_{bf}$$
$$= 33\text{ dBW} + 64\text{ dB} - 3\text{ dB} - 4\text{ dB} = 90\text{ dBW}$$

Carrier power at satellite antenna:

$$C' = \text{EIRP (earth station)} - L_p - L_u$$
$$= 90\text{ dBW} - 206.5\text{ dB} - 0.6\text{ dB} = -117.1\text{ dBW}$$

C/N_0 at the satellite:

$$\frac{C}{N_0} = \frac{C}{KT_e} = \frac{C}{T_e} \times \frac{1}{K} \qquad \text{where } \frac{C}{T_e} = C' \times \frac{G}{T_e}$$

Thus, $$\frac{C}{N_0} = C' \times \frac{G}{T_e} \times \frac{1}{K}$$

Expressed as a log,

$$\frac{C}{N_0} = C' + \frac{G}{T_e} - 10\log(1.38 \times 10^{-23})$$
$$= -117.1\text{ dBW} + (-5.3\text{ dBK}^{-1}) - (-228.6\text{ dBWK}) = 106.2\text{ dB}$$

Thus, $$\frac{E_b}{N_0} = \frac{C/f_b}{N_0} = \frac{C}{N_0} - 10\log f_b$$
$$= 106.2\text{ dB} - 10\,(\log 120 \times 10^6) = 25.4\text{ dB}$$

and for a minimum bandwidth system,

$$\frac{C}{N} = \frac{E_b}{N_0} - \frac{B}{f_b} = 25.4 - 10\log\frac{40 \times 10^6}{120 \times 10^6} = 30.2\text{ dB}$$

$$B = \frac{f_b}{\text{Number of bits per symbol}}$$

2) Downlink budget (expressed as log)

$$\begin{aligned}\text{EIRP (satellite transponder)} &= P_t + A_t - L_{\text{bo}} - L_{bf} \\ &= 10\text{ dBW} + 30.8\text{ dB} - 0.1\text{ dB} - 0.5\text{ dB} \\ &= 40.2\text{ dBW}\end{aligned}$$

Carrier power at ES antenna:

$$\begin{aligned}C' &= \text{EIRP} - L_p - L_d \\ &= 40.2\text{ dBW} - 205.6\text{ dB} - 0.4\text{ dB} = -165.8\text{ dBW}\end{aligned}$$

C/N_0 at the earth station receiver:

$$\frac{C}{N_0} = \frac{C}{KT_e} = \frac{C}{T_e} \times \frac{1}{K} \quad \text{where } \frac{C}{T_e} = C' \times \frac{G}{T_e}$$

Thus, $$\frac{C}{N_0} = C' \times \frac{G}{T_e} \times \frac{1}{K}$$

Expressed as a log,

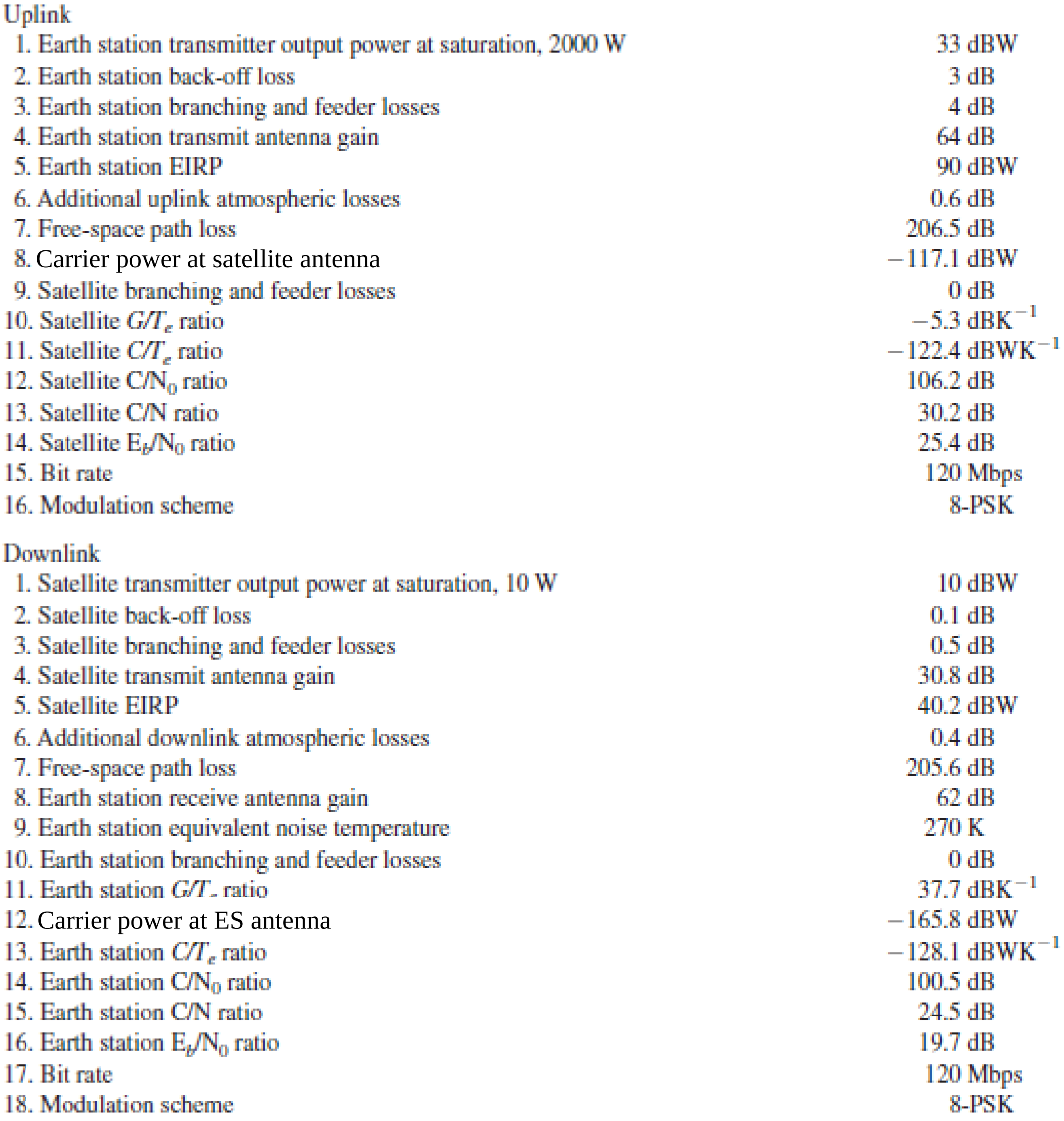
$$\begin{aligned}\frac{C}{N_0} &= C' + \frac{G}{T_e} - 10\log(1.38 \times 10^{-23}) \\ &= -165.8\text{ dBW} + (37.7\text{ dBK}^{-1}) - (-228.6\text{ dBWK}) = 100.5\text{ dB}\end{aligned}$$

$$\begin{aligned}\frac{E_b}{N_0} &= \frac{C}{N_0} - 10\log f_b \\ &= 100.5\text{ dB} - 10\log(120 \times 10^6) \\ &= 100.5\text{ dB} - 80.8\text{ dB} = 19.7\text{ dB}\end{aligned}$$

and for a minimum bandwidth system,

$$\frac{C}{N} = \frac{E_b}{N_0} - \frac{B}{f_b} = 19.7 - 10\log\frac{40 \times 10^6}{120 \times 10^6} = 24.5\text{ dB}$$

Link budget



Uplink	
1. Earth station transmitter output power at saturation, 2000 W	33 dBW
2. Earth station back-off loss	3 dB
3. Earth station branching and feeder losses	4 dB
4. Earth station transmit antenna gain	64 dB
5. Earth station EIRP	90 dBW
6. Additional uplink atmospheric losses	0.6 dB
7. Free-space path loss	206.5 dB
8. Carrier power at satellite antenna	-117.1 dBW
9. Satellite branching and feeder losses	0 dB
10. Satellite G/T_e ratio	-5.3 dBK^{-1}
11. Satellite C/T_e ratio	-122.4 dBWK^{-1}
12. Satellite C/N_0 ratio	106.2 dB
13. Satellite C/N ratio	30.2 dB
14. Satellite E_b/N_0 ratio	25.4 dB
15. Bit rate	120 Mbps
16. Modulation scheme	8-PSK
Downlink	
1. Satellite transmitter output power at saturation, 10 W	10 dBW
2. Satellite back-off loss	0.1 dB
3. Satellite branching and feeder losses	0.5 dB
4. Satellite transmit antenna gain	30.8 dB
5. Satellite EIRP	40.2 dBW
6. Additional downlink atmospheric losses	0.4 dB
7. Free-space path loss	205.6 dB
8. Earth station receive antenna gain	62 dB
9. Earth station equivalent noise temperature	270 K
10. Earth station branching and feeder losses	0 dB
11. Earth station G/T_e ratio	37.7 dBK^{-1}
12. Carrier power at ES antenna	-165.8 dBW
13. Earth station C/T_e ratio	-128.1 dBWK^{-1}
14. Earth station C/N_0 ratio	100.5 dB
15. Earth station C/N ratio	24.5 dB
16. Earth station E_b/N_0 ratio	19.7 dB
17. Bit rate	120 Mbps
18. Modulation scheme	8-PSK

Overall System Performance

- The overall E_b/N_0 includes the combined effects of the uplink ratio $(E_b/N_0)_\mathrm{u}$ and the downlink ratio $(E_b/N_0)_\mathrm{d}$.

$$\frac{E_b}{N_0}(\text{overall}) = \frac{(E_b/N_0)_u(E_b/N_0)_d}{(E_b/N_0)_u + (E_b/N_0)_d}$$

where all E_b/N_0 ratios are in **absolute** values.

The same formula is applied for overall C/N_0 ratio.

- As known for product-over-sum relationships, the smaller of the two numbers dominates. If one number is substantially smaller than the other, the overall result is approximately equal to the smaller of the two numbers.

For the illustrated example

$$\frac{E_b}{N_0}(\text{overall}) = \frac{(346.7)(93.3)}{346.7 + 93.3} = 73.5$$

$$= 10 \log 73.5 = 18.7 \text{ dB}$$

Satellite Applications: Navigational Satellites

Global Positioning System (GPS)

Global Positioning System (GPS)

- Global Navigation Satellite System (GNSS) refers to the multiple satellite systems used for worldwide navigation.
- The original GNSS was the U.S.'s Global Positioning System (GPS) and still is the most widely used across the globe (development start in 1973 and fully functional in 1994)

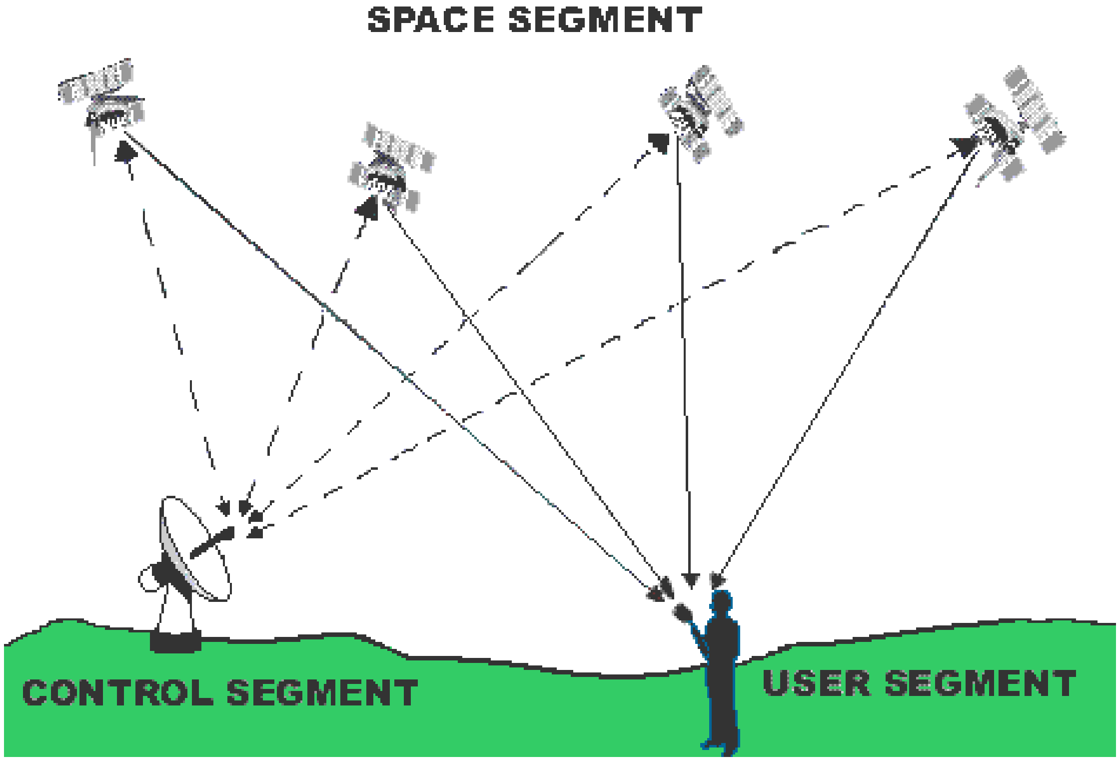
- The *Global Positioning System (GPS),* also known as Navstar, is a satellite-based navigation system that can be used by anyone with an appropriate receiver to determine her or his location on earth.

- The array of GPS satellites transmits accurate, time-coded information that permits a receiver to calculate its exact location in terms of the latitude and longitude on earth as well as the altitude above sea level.

GPS Segments

- The GPS consists of three major segments:

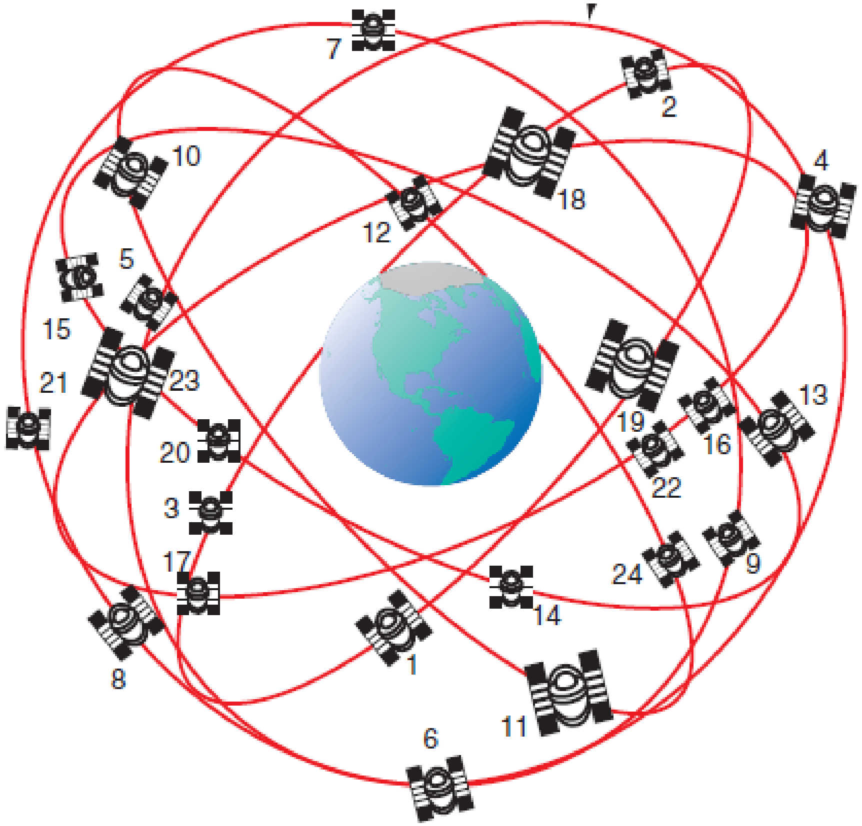
1) Space segment: constellation of 24 satellites
2) Control segment: provide ground-based facilities
3) User segment: calculate its position



GPS Segments (cont'd)

1) Space Segment

- The space segment is the network of satellites orbiting above the earth with transmitters that send highly accurate timing information to GPS receivers on earth (the receivers can be at land, sea, or air).



GPS Segments (cont'd)

1) Space Segment (cont'd)

- The **Navstar** consists of 24 main operational satellites plus multiple active spare satellites. The satellites are arranged in six orbits, each orbit containing three or four satellites.
- MEO orbits inclined at different degrees to the equator, between –55° +55° at an altitude of 10,898 mile (20,200 km).
- The orbital period for each satellite is approximately 12h.

- GPS satellites send timing pulses and set of codes that defines its location at any given time (on L-band downlink).
- The satellite's position data is updated once a day by the ground control station to ensure accuracy.

GPS Segments (cont'd)

2) Control Segment

- The control segment of the GPS refers to the various ground stations that monitor the satellites and provide control and update information.
- Navstar's master control station is operated by the U.S. Air Force in Colorado. Additional four monitoring and control stations are located in different U.S states.

- Control stations monitor the satellites and collect range information from each satellite. The information is sent back to the master control station, where all the information is collected and position data on each satellite is calculated.
- The master control station then transmits new position and clock data to each satellite on the S-band uplink once per day.

GPS Segments (cont'd)

3) User Segment (GPS receiver)

- A GPS receiver is a complex microwave receiver designed to pick up the GPS signals, decode them, and then compute the location of the receiver.
- The output is usually an LCD display giving latitude, longitude, and altitude information.

- GPS receivers are not only communication receivers but also sophisticated computers to compute the receiver position from the received data.

How GPS Works

- GPS receivers use Trilateration to determine its location.
- When it gets signals from at least 3 GPS satellites, the receiver should be able to calculate its approximate position (2D).
- The location determination is based on determining the distance to each satellite.

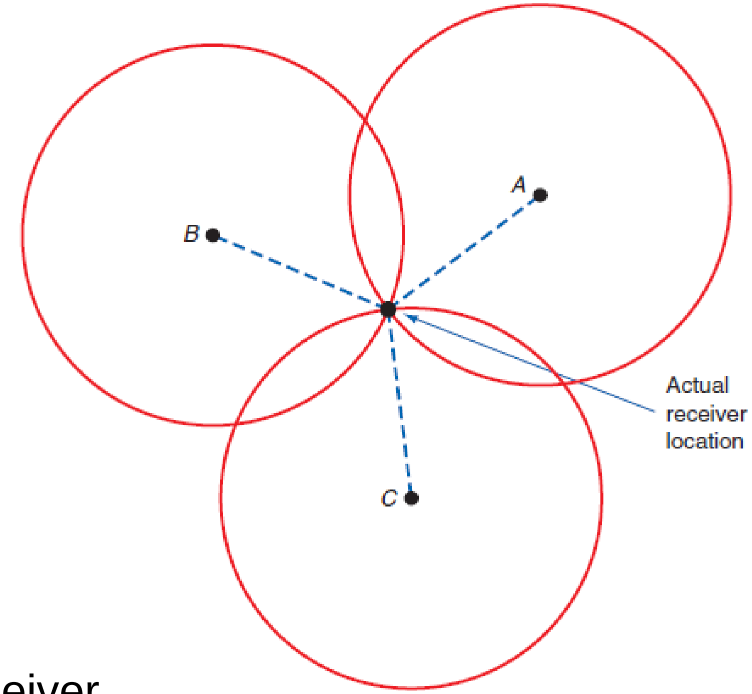
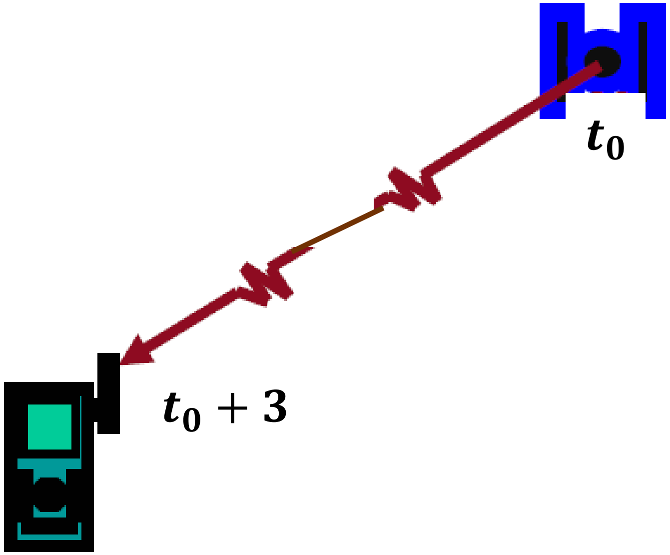


Fig. Trilateration method to locate a GPS receiver

Measuring distance to a Satellite

- The distance to each satellite is measured by measuring the time of arrival of the satellite signals and then computing distance based on the speed of radio waves [$3 \times 10^8 \mathrm{m/s}$] (with correction factors).



Ex: If a signal leaves a satellite at time "t_0", and picked up by the GPS receiver at time "t_0 +3", this means it takes 3 seconds to reach the GPS unit.

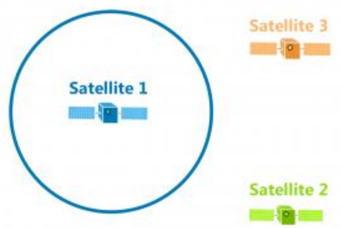
The distance between satellite and GPS unit is 3 times the speed of light.

Fig. Measuring distance between satellite and GPS receiver.

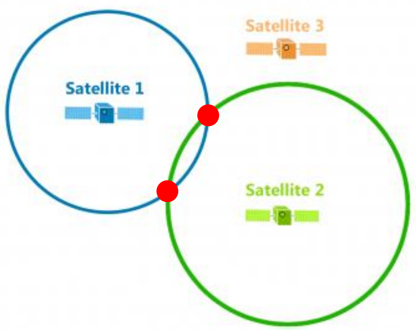
- **Correction factors**: There is a difference between the clock frequency in the GPS receivers and the clock in the satellite, therefore, the distance measurement must be corrected to account for the internal clock error.

GPS Trilateration

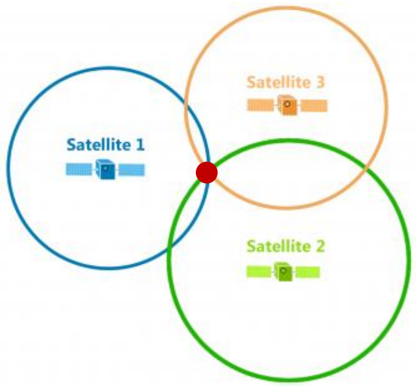
- Assume three satellites A, B, and C. The receiver first computes the distance from the receiver to satellite A. The distance from A is on a circle.
- Then the receiver calculates the distance to satellite B. That distance is defined along another circle.
- The two circles intersect at two points. One of those is the exact location, but we don’t know which until we get a third satellite reading.
- The distance from satellite C intersects with the other circles at only one point. That is the location of the receiver.



Distance to 1 satellite



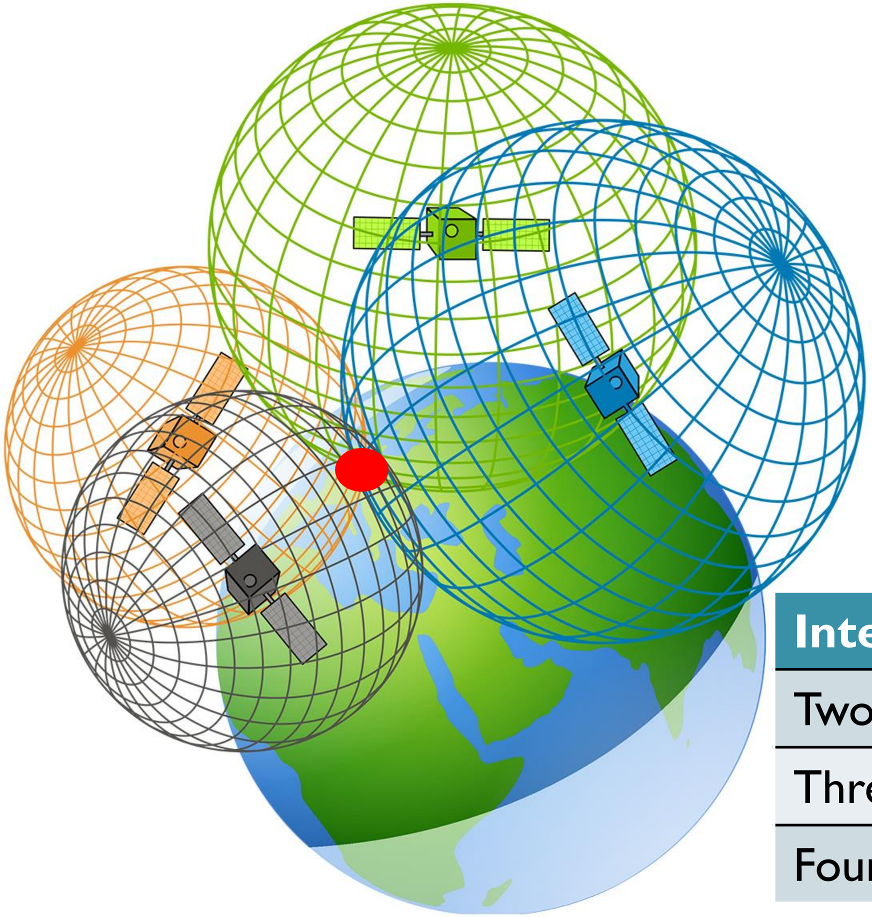
Distance to 2 satellites



Distance to 3 satellites

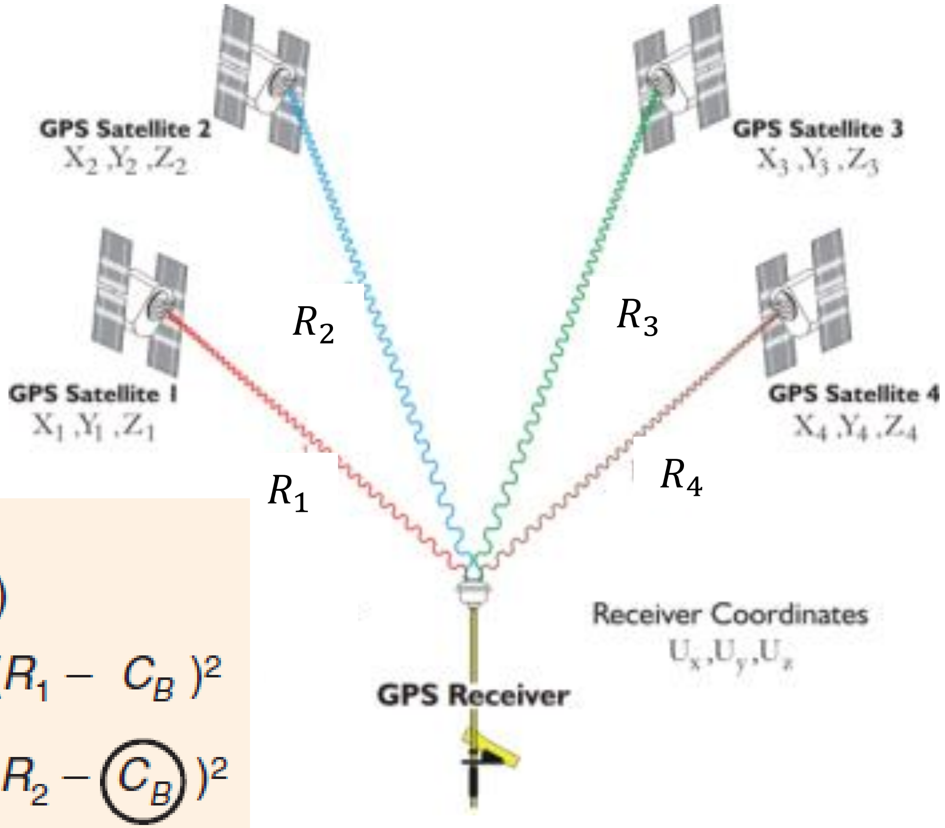
GPS Trilateration (cont'd)

- Actually, the distance is defined along a sphere and using a fourth satellite enables determining the altitude (3D position).



Intersection of	Equivalency	Result
Two spheres	circle	circle
Three spheres	circle ∩ sphere	two points
Four spheres	two points ∩ sphere	one point

GPS Trilateration (cont'd)



Compute position coordinates
(four equations with four unknowns)

$$(X_1 - U_X)^2 + (Y_1 - U_Y)^2 + (Z_1 - U_Z)^2 = (R_1 - C_B)^2$$

$$(X_2 - \enclose{circle}{U_X})^2 + (Y_2 - \enclose{circle}{U_Y})^2 + (Z_2 - \enclose{circle}{U_Z})^2 = (R_2 - \enclose{circle}{C_B})^2$$

$$(X_3 - \enclose{circle}{U_X})^2 + (Y_3 - \enclose{circle}{U_Y})^2 + (Z_3 - \enclose{circle}{U_Z})^2 = (R_3 - \enclose{circle}{C_B})^2$$

$$(X_4 - \enclose{circle}{U_X})^2 + (Y_4 - \enclose{circle}{U_Y})^2 + (Z_4 - \enclose{circle}{U_Z})^2 = (R_4 - \enclose{circle}{C_B})^2$$

Solve for position coordinates
(U_X, U_Y, U_Z) and clock bias (C_B)

2D Trilateration

Example:

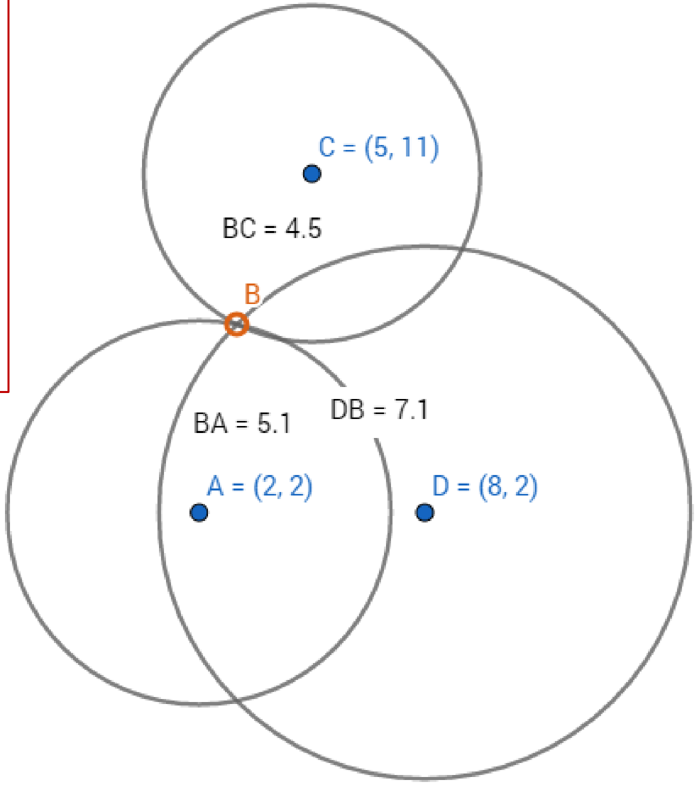
Find the location of point B ((x,y)), given location of three points A, C, and D and distances between the three known points and B are:

$$d_A \cong 5.1 \text{ km}$$

$$d_C \cong 4.5 \text{ km}$$

$$d_D \cong 7.1 \text{ km}$$

(assume A,B,C, and D lie in the same horizontal plane)



Solution:

2D Trilateration (cont'd)

Equations of 3 circles:

$$(x - x_A)^2 + (y - y_A)^2 = (d_A)^2$$

$$(x - x_C)^2 + (y - y_C)^2 = (d_C)^2$$

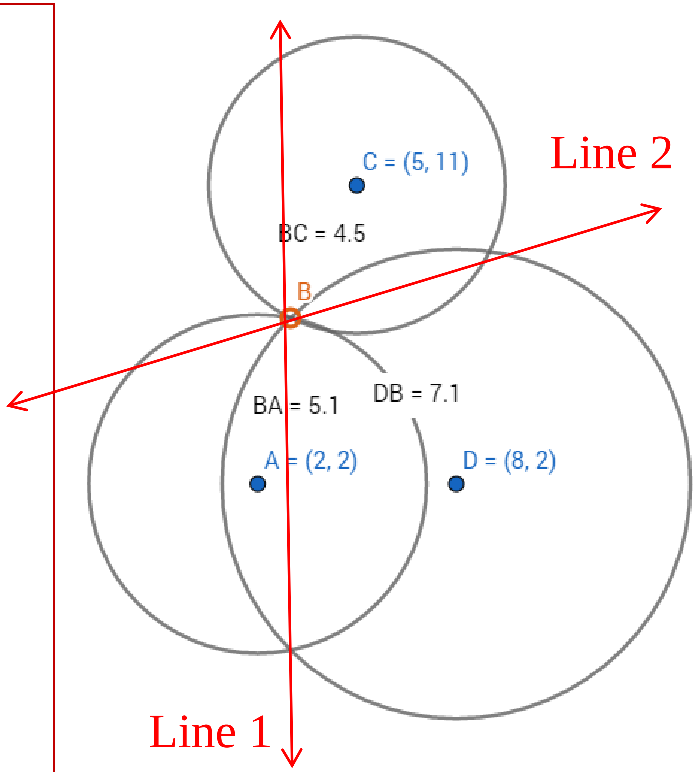
$$(x - x_D)^2 + (y - y_D)^2 = (d_D)^2$$

Substitute:

Eq1: $(x - 2)^2 + (y - 2)^2 = (5.1)^2$

Eq2: $(x - 5)^2 + (y - 11)^2 = (4.5)^2$

Eq3: $(x - 8)^2 + (y - 2)^2 = (7.1)^2$



Subtracting any two circle equations gives a linear equation for the line passing through their intersection points.

e.,g., Eq1-Eq3: gives line 1

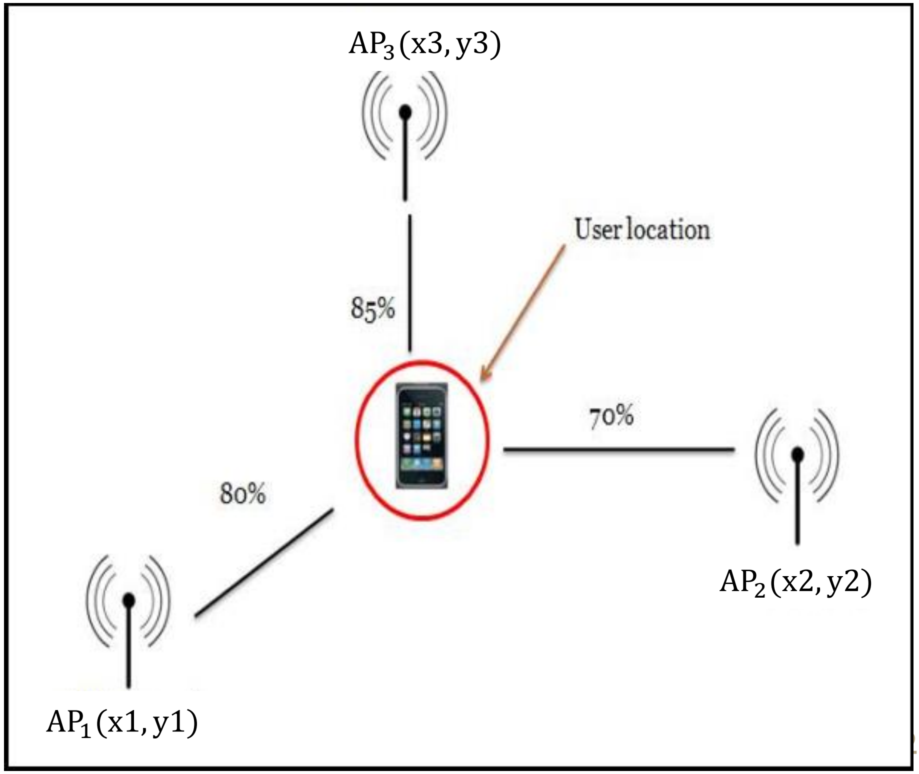
Eq2-Eq3: gives line 2

Line 1 and Line 2 are intersected at the required point B. So, solving their equations will give (x,y) position of B. [check your answer: (3,7)]

Indoor Positioning

- GPS Requires a sufficiently clear view of the sky in order to obtain a position fix, so the user must be outside and can’t use GPS indoor.
- Indoor positioning can be achieved by using the concept of 2D Trilateration by exploiting receiving Wi-Fi signals from at least three access points (APs) with known position and distance.

- Distance to each AP can be determined from its received signal strength (RSS)



GPS Accuracy and Sources of Errors

- A well-designed GPS receiver can achieve a horizontal accuracy of 3 meters or better and vertical accuracy of 5 meters or better 95% of the time. Augmented GPS systems can provide sub-meter accuracy.

GPS Sources of Errors

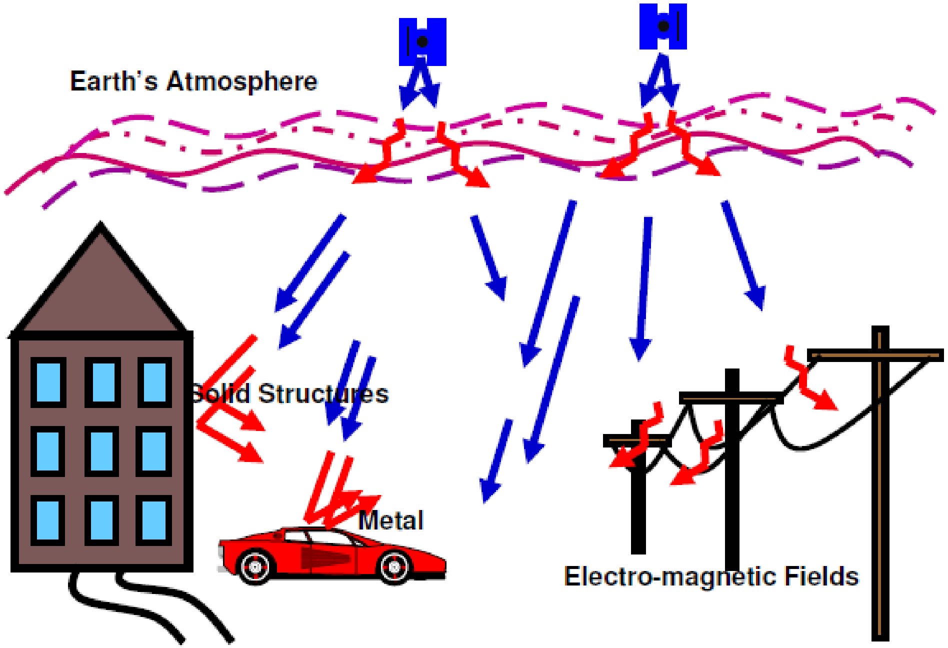
- **Satellite Clock Errors:** Caused by slight discrepancies in each satellite's four atomic clocks. Errors are monitored and corrected by the Master Control Station.

- **Orbit Errors:** Satellite orbits vary due to gravitational pull and solar pressure fluctuations. Orbit errors are also monitored and corrected by the Master Control Station.

Sources of GPS Errors (cont'd)

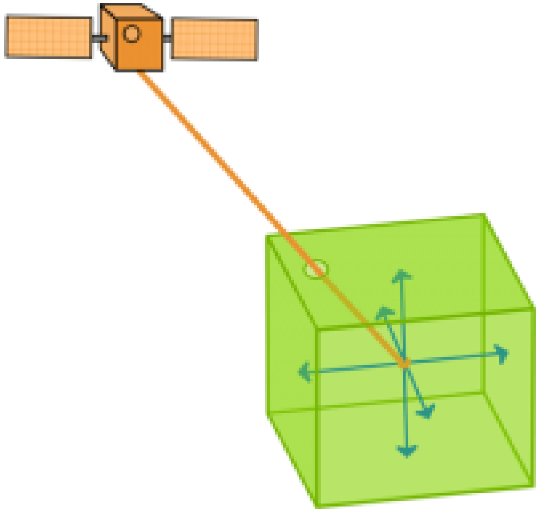
- **Atmospheric interference :** The troposphere and ionosphere can change the speed of propagation of a GPS signal. Due to atmospheric conditions, the atmosphere refracts the satellite signals as they pass through on their way to the earth's surface.

- **Multipath interference :** caused by reflected radio signals from surfaces near the GPS receiver. Multipath is difficult to detect.



Sources of GPS Errors (cont'd)

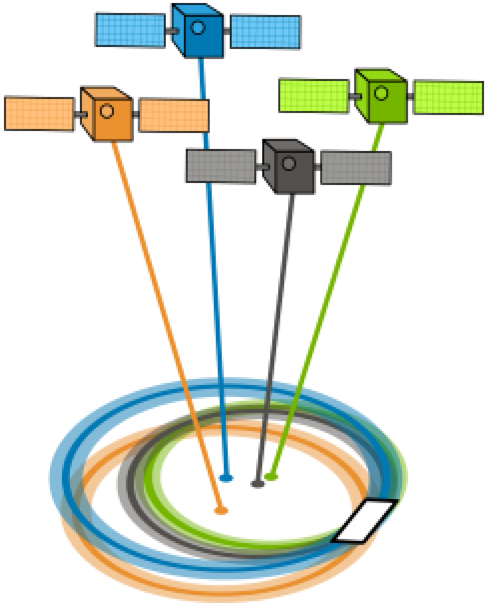
- **Selective Availability:** (S/A) was the intentional degradation of the satellite signals by a time varying bias. S/A is controlled by the DoD to limit accuracy for non - U.S. military and government users and was originally instituted for security reasons.



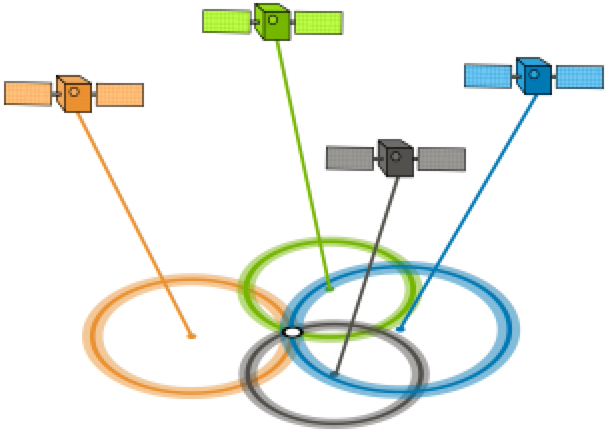
- **Number of satellites visible:** The more satellites the receiver can "see", the better the accuracy. The clearer the view, to the receiver the better the reception.

Sources of GPS Errors (cont'd)

- **Satellites geometry:** This refers to the relative position of the satellites at any given time. Ideal satellite geometry exists when the satellites are located at wide angles relative to each other. Poor geometry exists when the satellites are located in a line or in a tight grouping.



Bad satellite geometry



Good satellite geometry

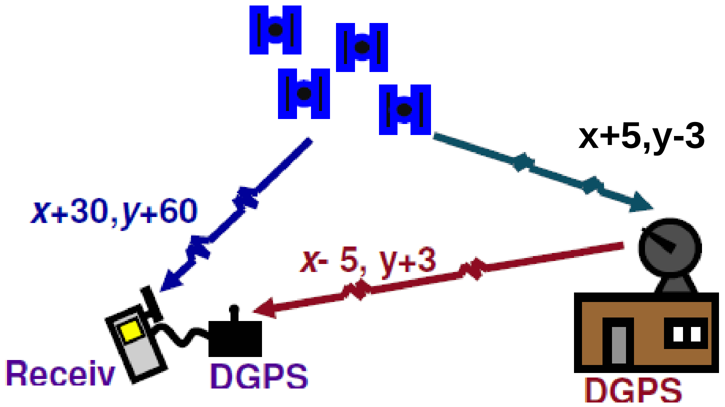
Enhanced GPS

a number of services have been developed to improve on the accuracy of the GPS.

Differential GPS (DGPS)

- DGPS uses a fixed station with precise known location. This station monitors all satellites and compares location data from the satellite to its known position. It determines any errors in position and transmits these errors to GPS receivers, where the error data updates the received data to give a more accurate position.

- The receiver must be DGPS-enabled to receive the corrective data. Use of DGPS improves the accuracy with an error within 3 to 6 ft.



DGPS correction =
x+(30-5) and *y*+(60+3)
True coordinates =
x+25, *y*+63

True
coordinates =
x+0, *y*+0
Correction = *x*-
5, *y*+3

Enhanced GPS (cont'd)

Wide Area Augmentation System (WAAS)

- Can be thought as as a highly advanced differential GPS. But instead of using ground based transmitters to broadcast position correction information, WAAS uses its own geostationary satellites in fixed orbit over North America.

- The WAAS consists of about 25 ground stations around the United States with precisely known locations and two coastal stations that collect all the data from the other stations. The collected data is used to determine all errors, and then differential correction signals are transmitted up to one of two geosynchronous satellites that in turn transmit the correction signals to GPS receivers.

- As with DGPS, the receiver must be WAAS-enabled to receive the corrective data. Use of WAAS improves the accuracy with an error of less than 3 ft.

Applications of GPS

Aviation

Marine

Farming

Science

Surveying

Military

Worldwide GNSS

- The success of GPS encouraged other countries to build their own GNSS.
- Russia GLONASS (start in 1995) (24 satellites at 11,890 miles).
- China is building its own system, called Compass (30 satellites at 13,140 miles and 5 geostationary satellites).
- The European Union (EU) is building its own system, called Galileo (30 satellites at 14,430 miles).
- India also plans its own GNSS, called IRNSS. It will use 7 geostationary satellites, for coverage mainly around India and the surrounding area.
- Japan is building a 3-satellite system called QZSS that is a supplement to GPS.

- All the GNSSs can complement one another to provide increased accuracy. Many GNSS receivers are capable of receiving both GPS and one or more other GNSS signals, and combining them for improved precision.

Thanks for attention