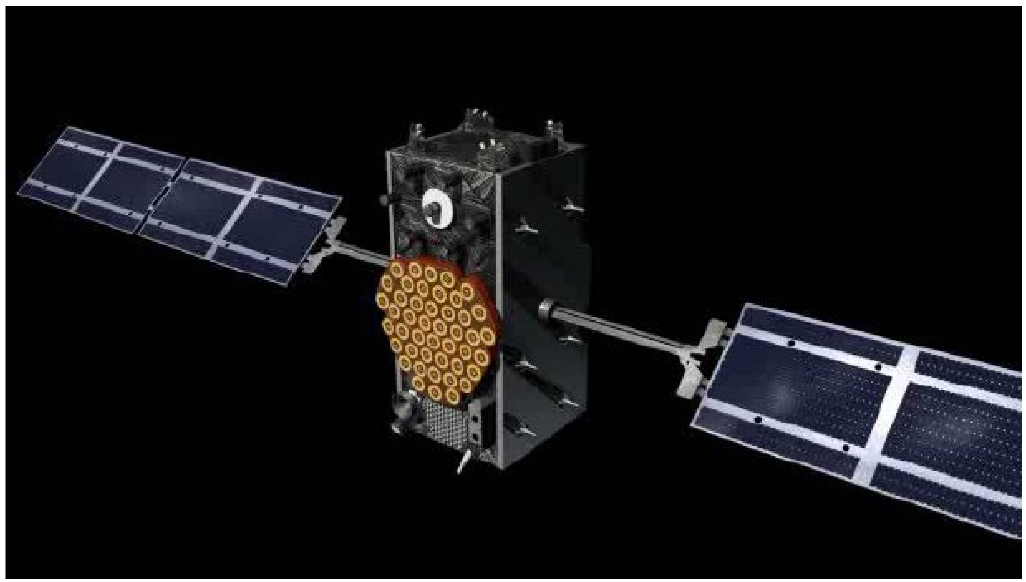
Chapter 6. Satellite Communications



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Bsc Degree on Telecommunication 2023-2024
Dpt. Communication Engineering
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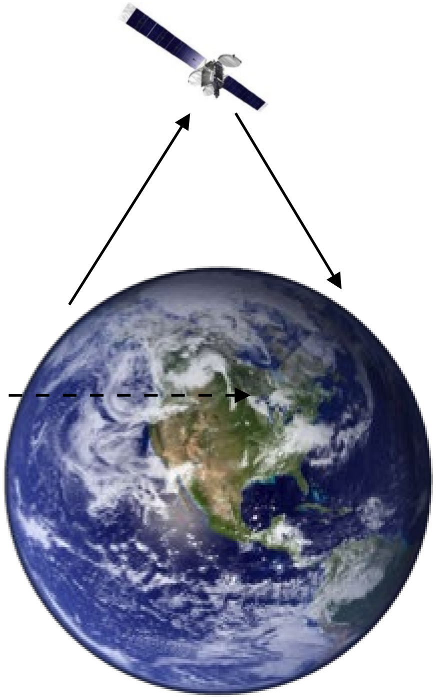
Basics

Definitions - ITU Radio Regulations – Article 1:

- Space radiocommunication: Any radiocommunication involving the use of one or more space stations or the use of one or more reflecting satellites or other objects in space.



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Basics

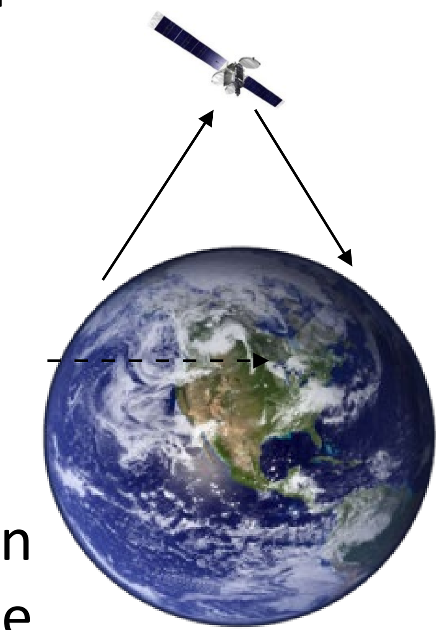
Radio Services – Applications:

- Fixed-satellite service: A radio-communication service between earth stations at given positions, when one or more satellites are used; the given position may be a specified fixed point or any fixed point within specified areas. In some cases this service includes satellite-to-satellite links.
- Mobile-satellite service A radio-communication service
  - between mobile earth stations by means of one or more space stations. This service may also include feeder links necessary for its operation; or
  - between mobile earth stations and one or more space stations, or between space stations used by this service.

Basics

Radio Services – Applications:

- Broadcasting-satellite service: A radio-communication service in which signals transmitted or retransmitted by space stations are intended for direct reception by the general public. In the broadcasting-satellite service, the term “direct reception” shall encompass both individual reception and community reception.
- Radiodetermination-satellite and Radionavegation services: Radio-communication services for the purpose of radiodetermination or radionavegation involving the use of one or more space stations. These services may also include feeder links necessary for the own operation.



Basics

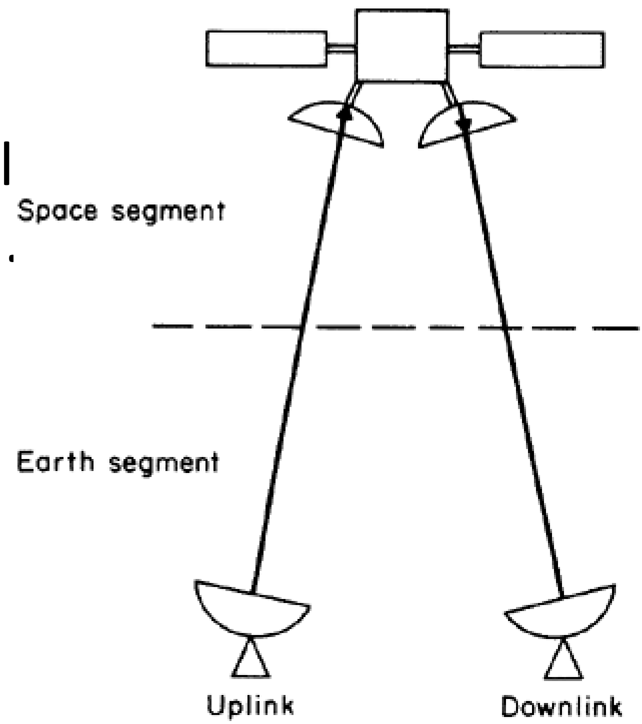
Radio Services – Applications:

- Satellite Broadband Internet access: Internet access provided through communication satellites.
  - Since the satellite Internet service does not require the deployment of cable networks, it constitutes in many cases the only way to provide broadband services in any area, especially for rural homes and businesses.
- Satellite Broadband Internet access: is Internet access provided through communication satellites. Modern consumer grade satellite Internet service is typically provided to individual users through:
  - Geostationary satellites using Ku band
  - New satellite internet constellations developed in low-earth orbit to enable low-latency internet access from space.

Basics

Basic Components:

- Space Segment: Includes satellite subsystems, components used to launch the satellites and ground equipment and facilities to control the satellite (Tracking, Telemetry, Command, and Monitoring, TTC&M, subsystem).
- Earth Segment: Consists of an ensemble of terrestrial equipment and facilities for the transmission, reception and processing of signal sent to or received from the satellite subsystem.
- Links: The communication paths established from one terminal to another:
  - Uplink: Earth station → Satellite station
  - Downlink: Satellite station → Earth station.
- Orbit: The stable curved path followed by an artificial satellite in its motion around the Earth under the influence of gravitation.



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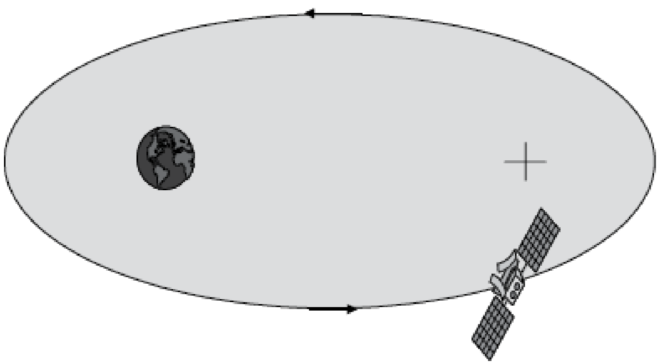
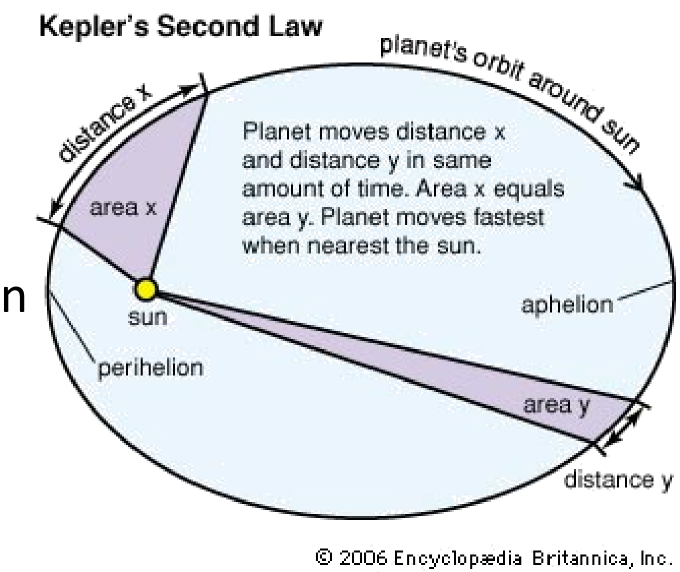
Orbits

Fundamentals:

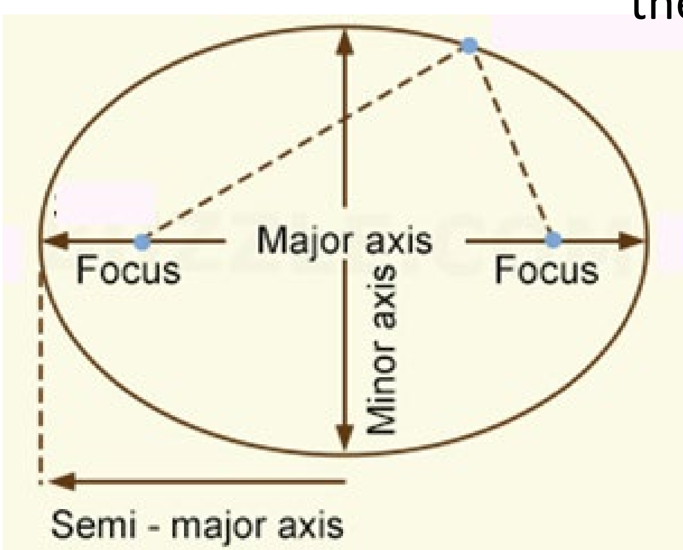
- The orbits follow the 3 Kepler laws



- Orbits are elliptical. Earth in one focus. Normally circular orbits used (particular case of elliptical)



- For equal time intervals, the satellite sweeps out equal areas in the orbital plane



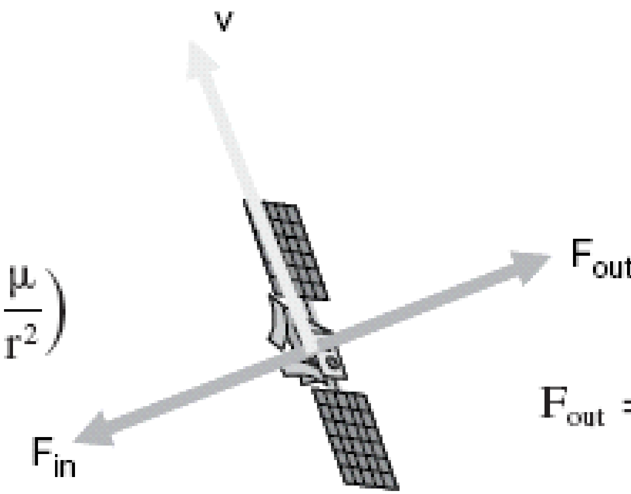
- The square of the periodic time of orbit is proportional to the cube of the mean distance between the earth and the satellite (lower orbit -> lower period -> faster movement): Sets the orbital period

Orbits

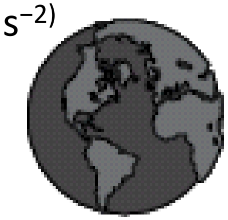
Fundamentals:

- Most important Forces:
  - m: satellite mass
  - μ: standard gravitational parameter = GM
  - M: mass of the Earth , $M=5.9736\times10^{24}$ kg
  - G: *G* is the universal gravitational constant ($G = 6.67\times10^{-11}$ m^3 kg^{-1} s^{-2})

$$F_{in} = m\left(\frac{\mu}{r^2}\right)$$



$$F_{out} = m\left(\frac{v^2}{r}\right)$$



- r: distance between Earth center and satellite
- v: velocity

- At a given distance r, escape velocity is the speed at which the kinetic energy plus the gravitational potential energy is zero. It is the speed needed to "break free" from the gravitational attraction of a massive body, without further propulsion.
- For a spherically symmetric body, the escape velocity at a given distance is calculated by the formula

$$v_e = \sqrt{\frac{2GM}{r}},$$

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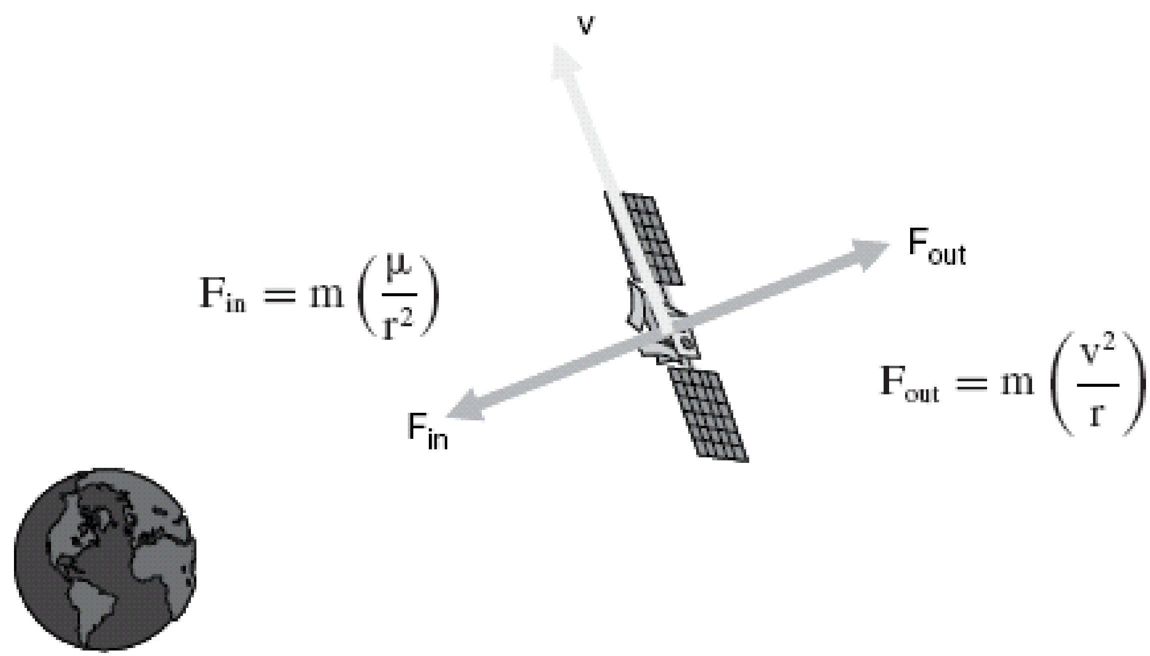
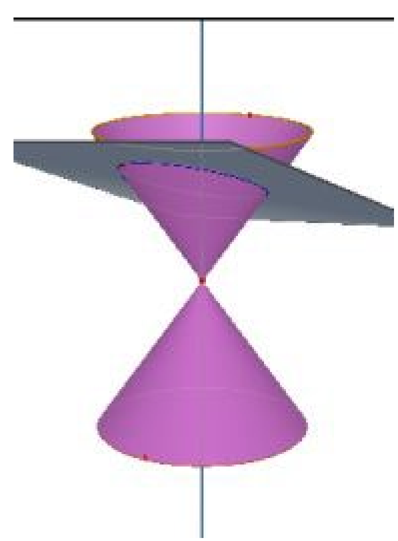
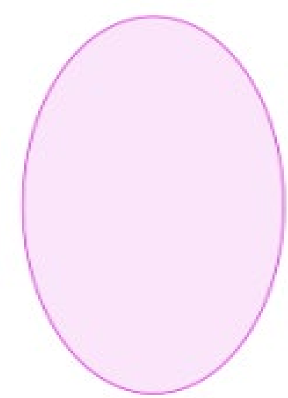
Orbits

Fundamentals:

- When the propulsion ceases at the launch of a satellite: If $v < v_e$ the satellite trajectory (orbit) will follow an elliptical conic section with focus on the center of the Earth (Solve the equations of motion of Newton)



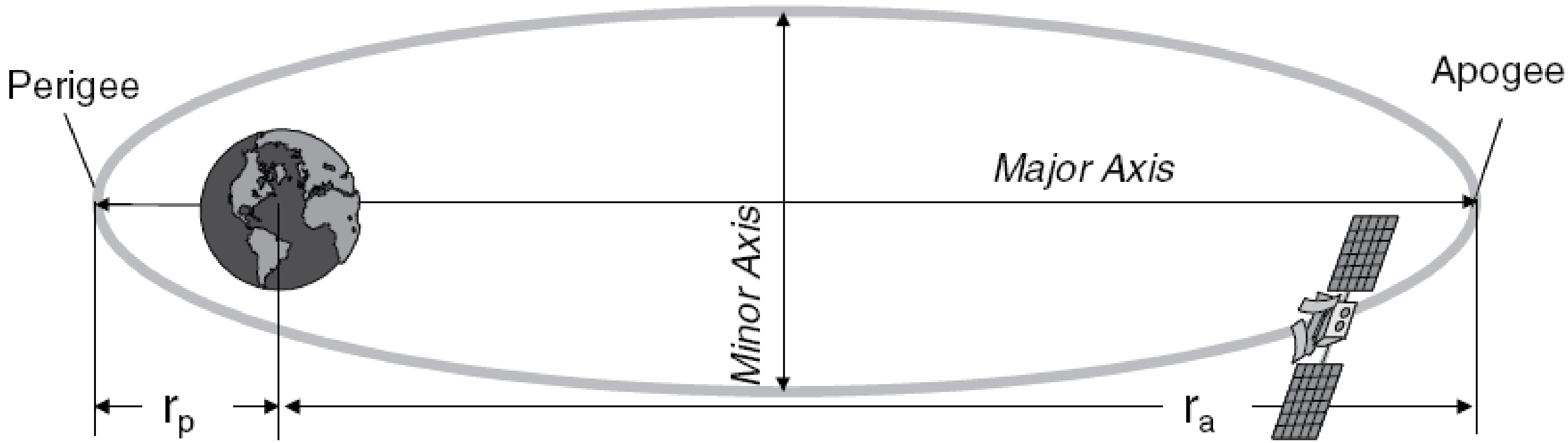




Orbits

Fundamentals:

- Elliptic orbits parameters



- Eccentricity (ratio between the axes of the ellipse)
  - Elliptical 0 <e <1
  - Circular 0

$$e = \frac{r_a - r_p}{r_a + r_p}$$

- Tilt:
  - Equatorial orbits
  - Inclined: An orbit whose inclination in reference to the equatorial plane is not zero degrees
  - Polar: An orbit that passes above or nearly above both poles of the planet on each revolution. Therefore it has an inclination of (or very close to) 90 degrees.

Orbits

Fundamentals:

- Circular orbits parameters
  - If $v = \sqrt{\frac{\mu}{r}}$ then the orbit is circular

$$Periode = 2\pi \frac{\mu}{v_c^3}$$

H (km)	r (km)	Velocity (km/s)	Period (s)	Period (hr	min)
500	6.878	7,613	5.677	1	35
800	7.178	7,452	6.052	1	41
1.400	7.778	7,159	6.827	1	54
5.000	11.378	5,919	12.079	3	21
10.400	16.778	4,874	21.628	6	00
15.000	21.378	4,318	31.107	8	38
35.786	42.164	3,075	86.164,1	23	56 minutes 4 seconds

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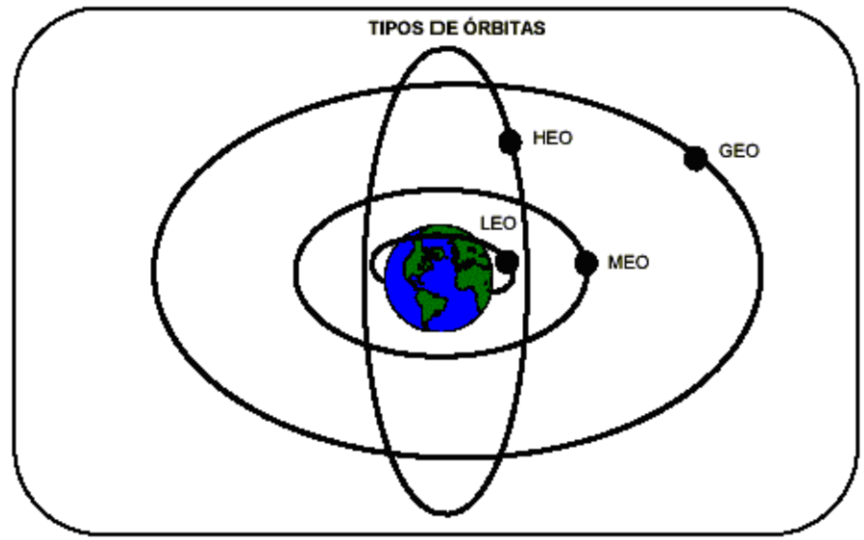
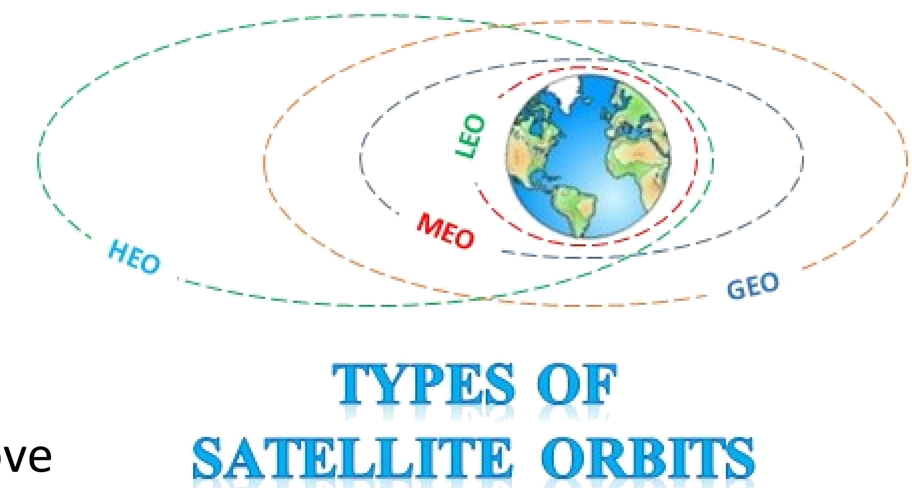
Orbits

Types of Orbits. Altitude classifications:

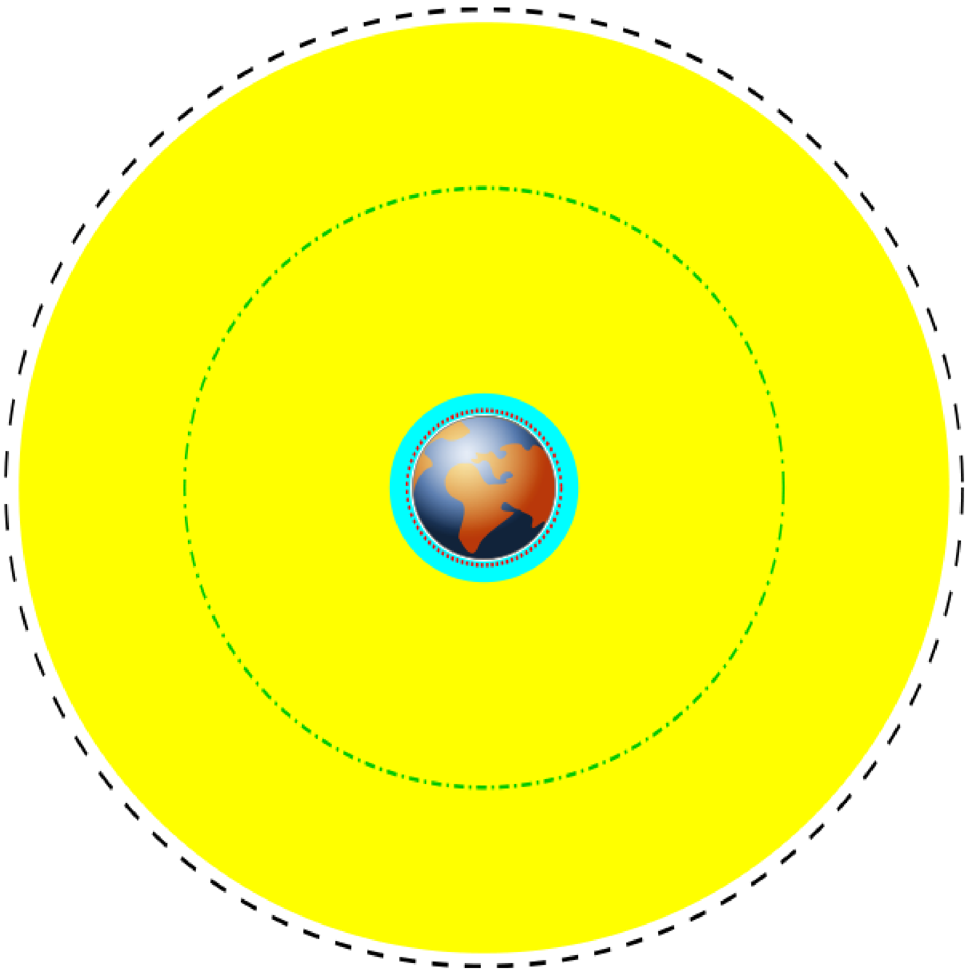
- Low Earth orbit (LEO): Circular geocentric orbits ranging in altitude from 160 to 2500 km
- Medium Earth orbit (MEO): Circular orbits ranging in altitude from 10000 to 20000 km. Van Allen Radiation Belts delimit the orbit borders for MEO and LEO
- Geosynchronous Orbit (GEO): Geocentric circular orbit with an altitude of 35,786 kilometres (22,236 mi). The period of the orbit equals one sidereal day, coinciding with the rotation period of the Earth. The speed is approximately 3,000 metres per second .
- High Earth orbit (HEO): Geocentric orbits above the altitude of geosynchronous orbit 35,786 km.





Orbits

Types of Orbits. Altitude classifications:



----- ISS International Space Station: h = 400 km

Orbitas LEO : h = 600-2000 km

Orbitas MEO : h = 3000-30000 km

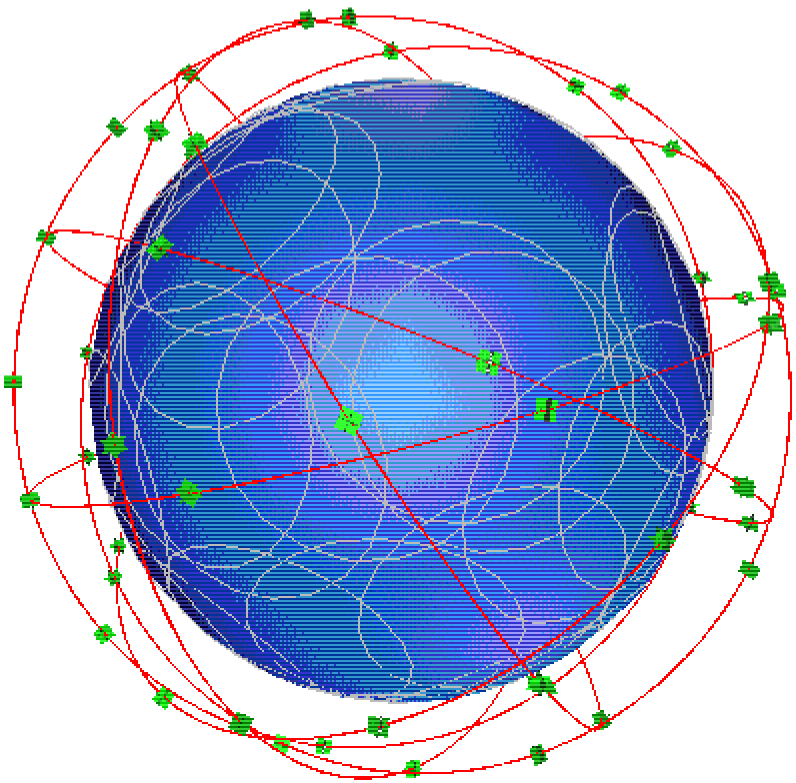
----- Global Positioning System (GPS): h = 20000 km

---- GEO : h=35787km

Orbits

Types of Orbits. Low Earth Orbits LEO

- Advantages:
  - Small distance-> small loses and delays
  - No need to be equatorial orbits-> Polar coverage
  - Less power and smaller antennas->smaller satellites, cheaper to build and to launch.
- Disadvantages:
  - No fixed location.
  - An earth terminal sees one satellite for 8 to 10 minutes.
  - Earth terminal tracking or no directional antennas
  - For global coverage many satellites needed (12 to 66)

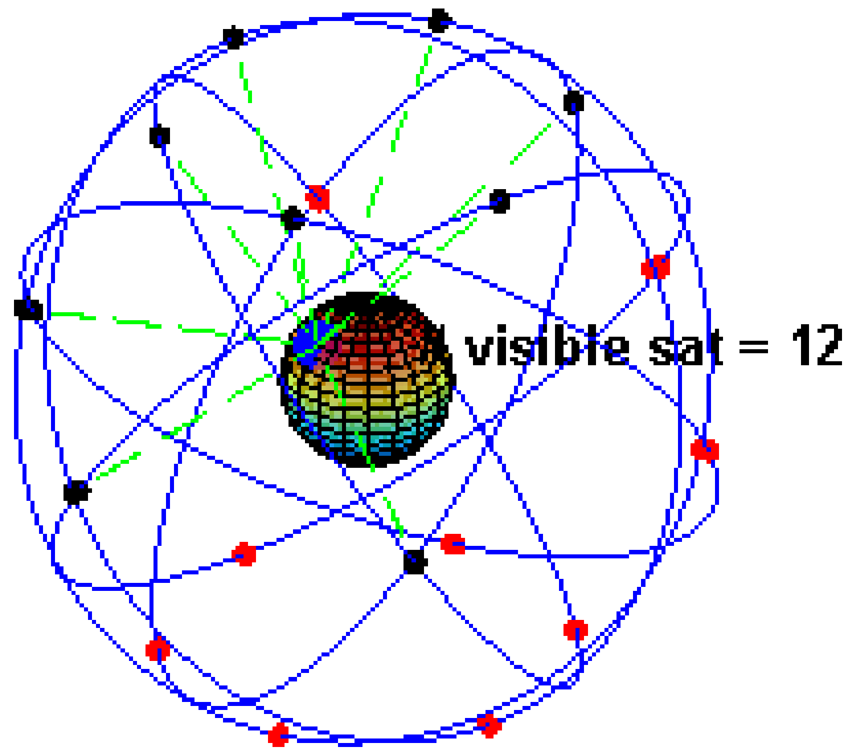


- Mainly used for mobile communications and new satellite broadband internet constellations developed in low-earth orbit to enable low-latency internet access from space

Orbits

Types of Orbits. Medium Earth Orbits MEO

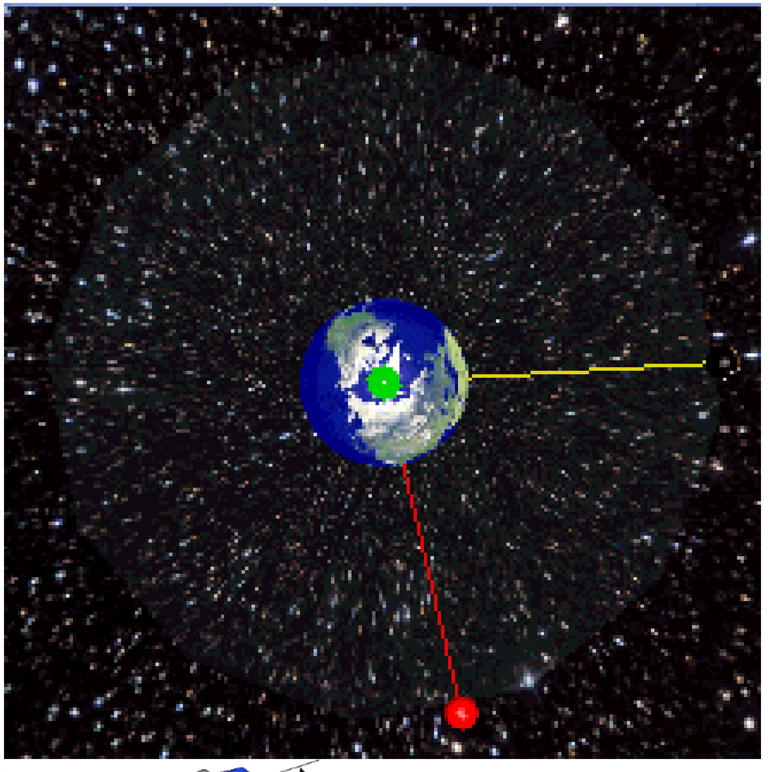
- In many aspects similar to LEO.
- One or two hours of observation.
- Used for Positioning and navigation (GPS and Galileo), meteorological measurements and remote sensing.
- GPS: 24 satellites, 12-hour circular orbits, altitude 20160 km
- Galileo: 27 satellites, 12-hour circular orbits, altitude 23222 km

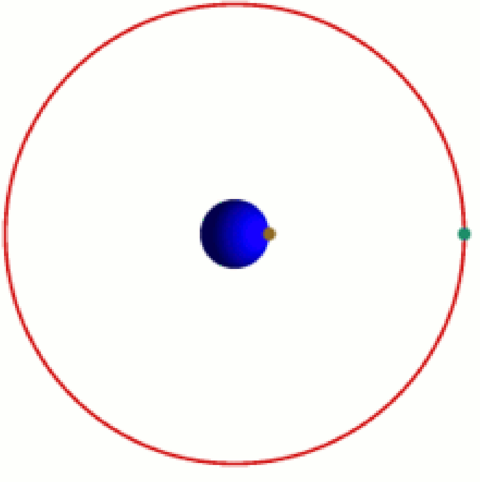


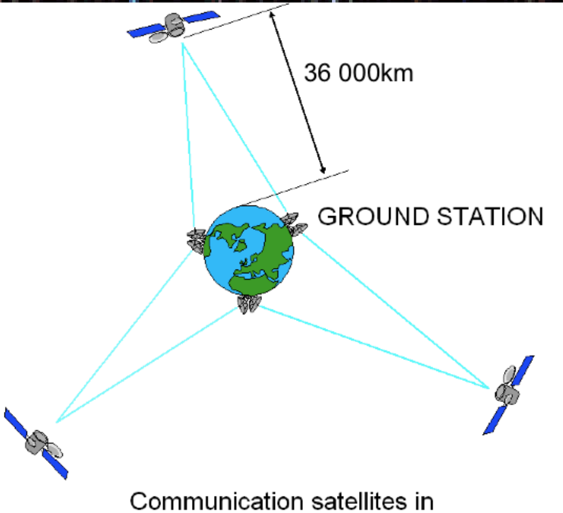
Orbits

Types of Orbits. Geostationary Orbits GEO

- Period equals rotation period of earth and in the same direction.
- Equatorial orbit
- Satellite seems to be fixed in the sky.
- Orbital radius 42164 km.
- Height over earth 42164-6378=35786 km (≈36000 km)
- The number of satellites in orbit is limited (2-5 °)
- Advantages:
  - "Fixed" position
  - Large coverage





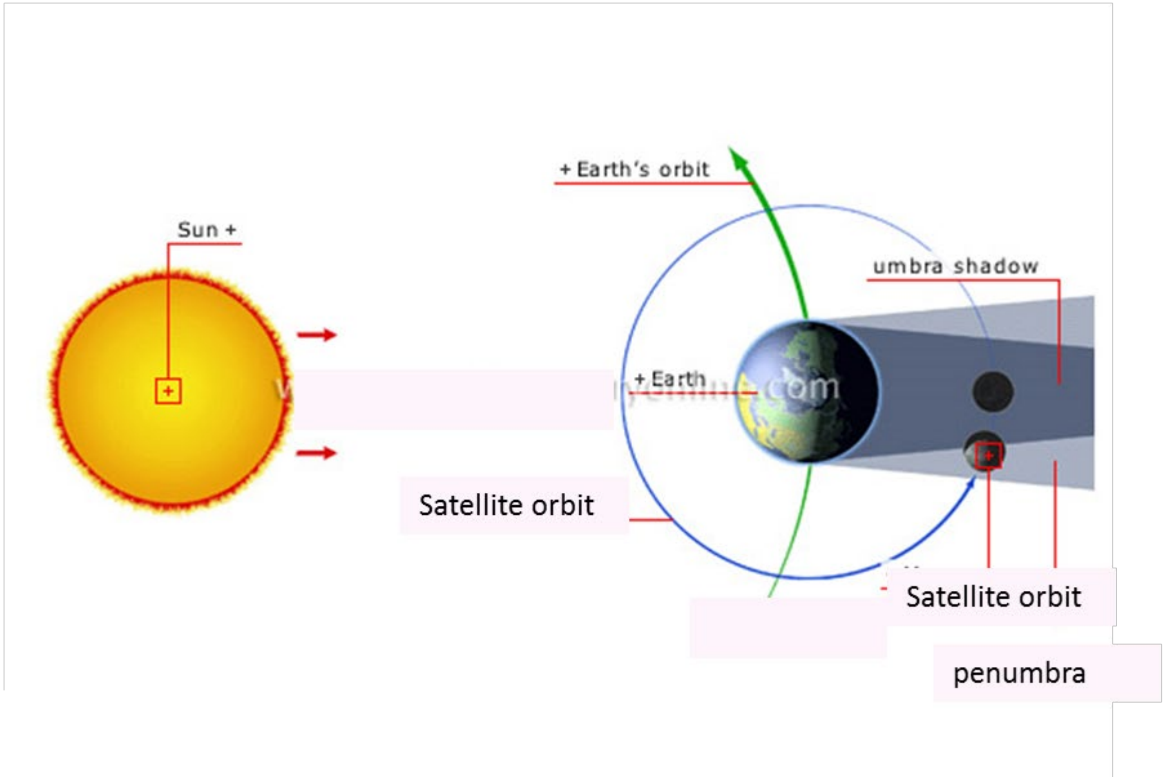


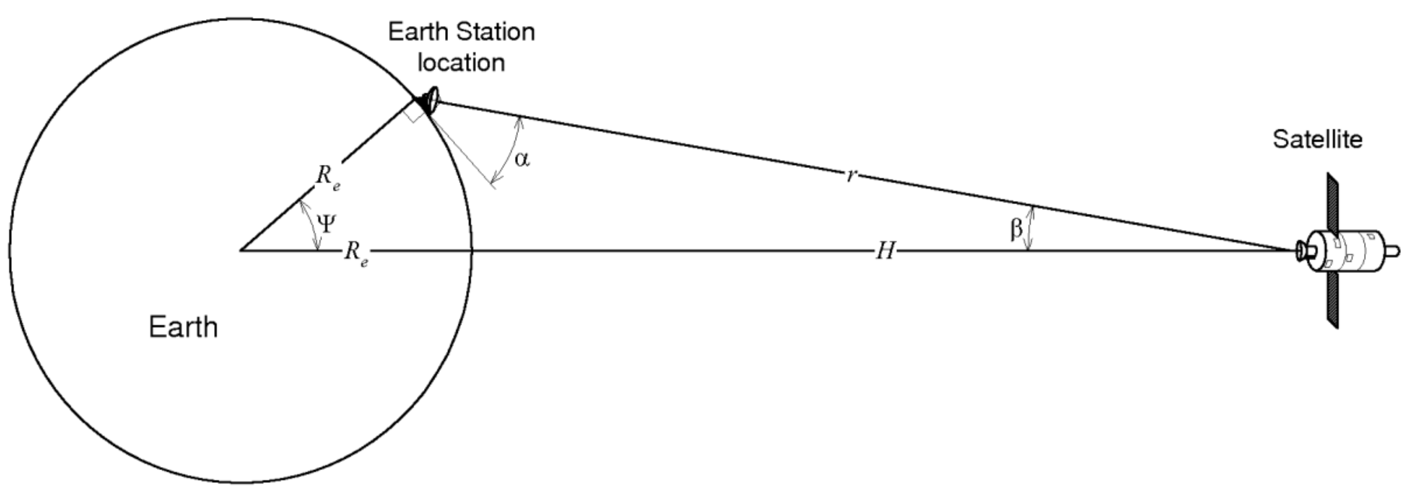
Communication satellites in geostationary orbits

Orbits

Types of Orbits. Geostationary Orbits GEO

- Disadvantages:
    - Satellite Eclipse

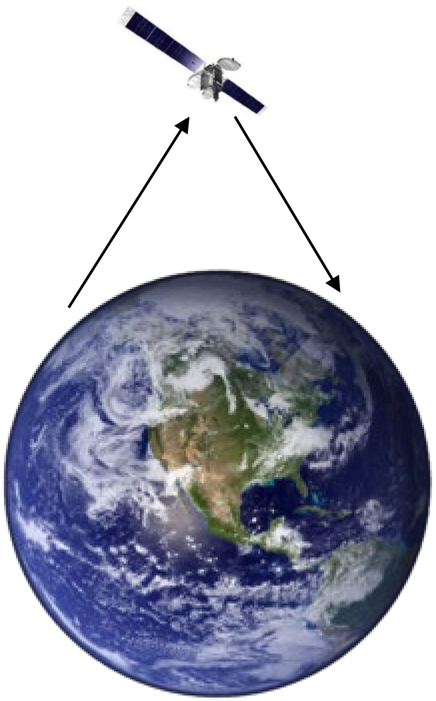




Orbits

Types of Orbits. Geostationary Orbits GEO

- Disadvantages:
  - Satellite Eclipse
  - Delay (latency)

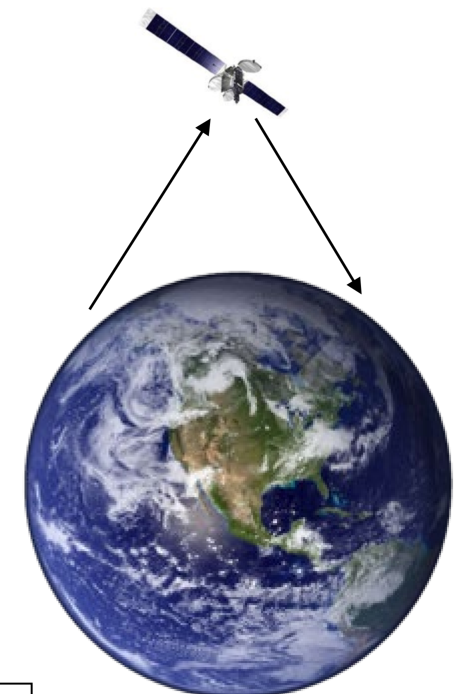


260 ms in a single hop (up and down)

Orbits

Types of Orbits. Geostationary Orbits GEO

- Disadvantages:
  - Satellite Eclipse
  - Delay
  - Attenuation



Path Losses

Example of free space loss:
14 GHz satellite link:

L_{FS} = 92.4 +20 log f +20 log r

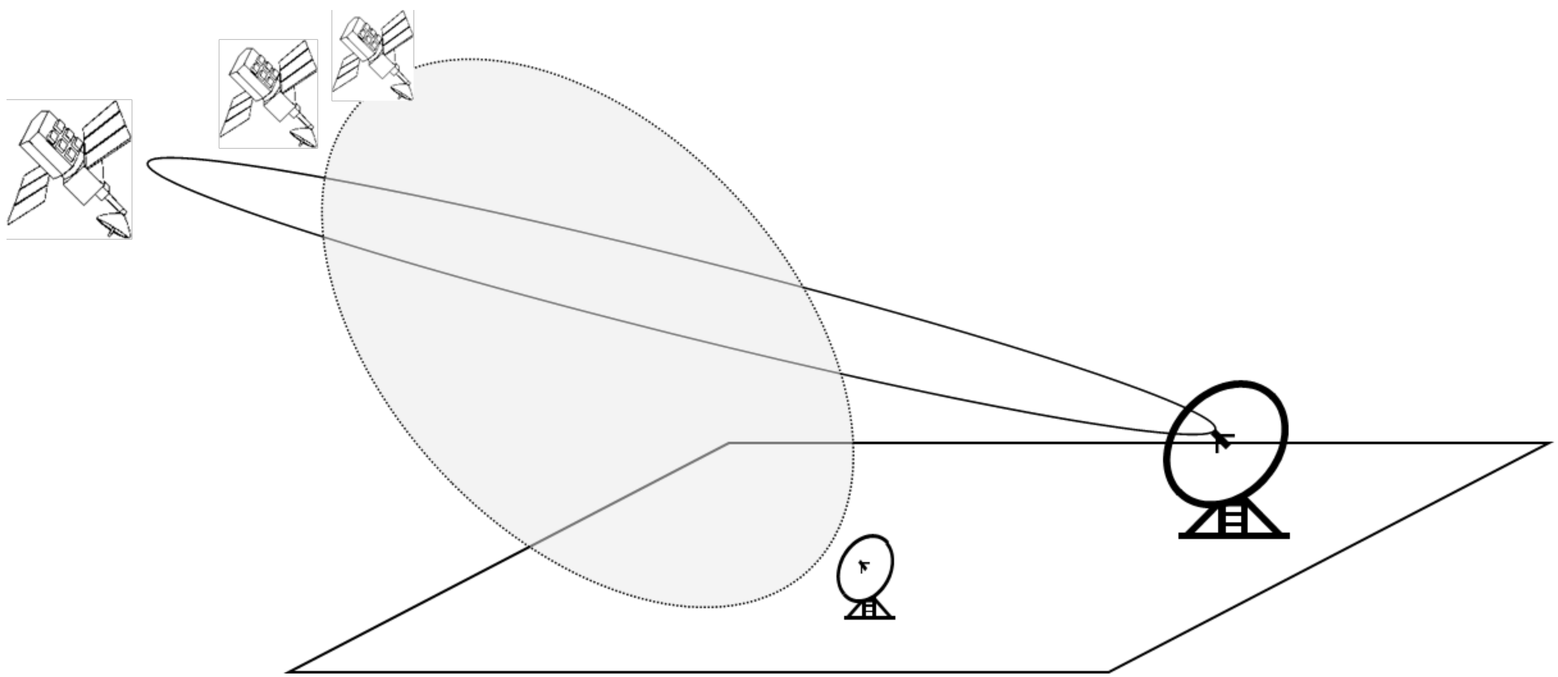
= 92.4 + 20 log 14 + 20 log 40 10^3 = 211.4 dB

- Serious problem in the space vehicle equipment
- Problem of interference with other services

Orbits

Types of Orbits. Geostationary Orbits GEO

- Disadvantages:
  - Satellite Eclipse
  - Delay
  - Attenuation
  - Orbital Saturation



Orbits

Types of Orbits. Geostationary Orbits GEO

- Disadvantages:
  - Satellite Eclipse
  - Delay
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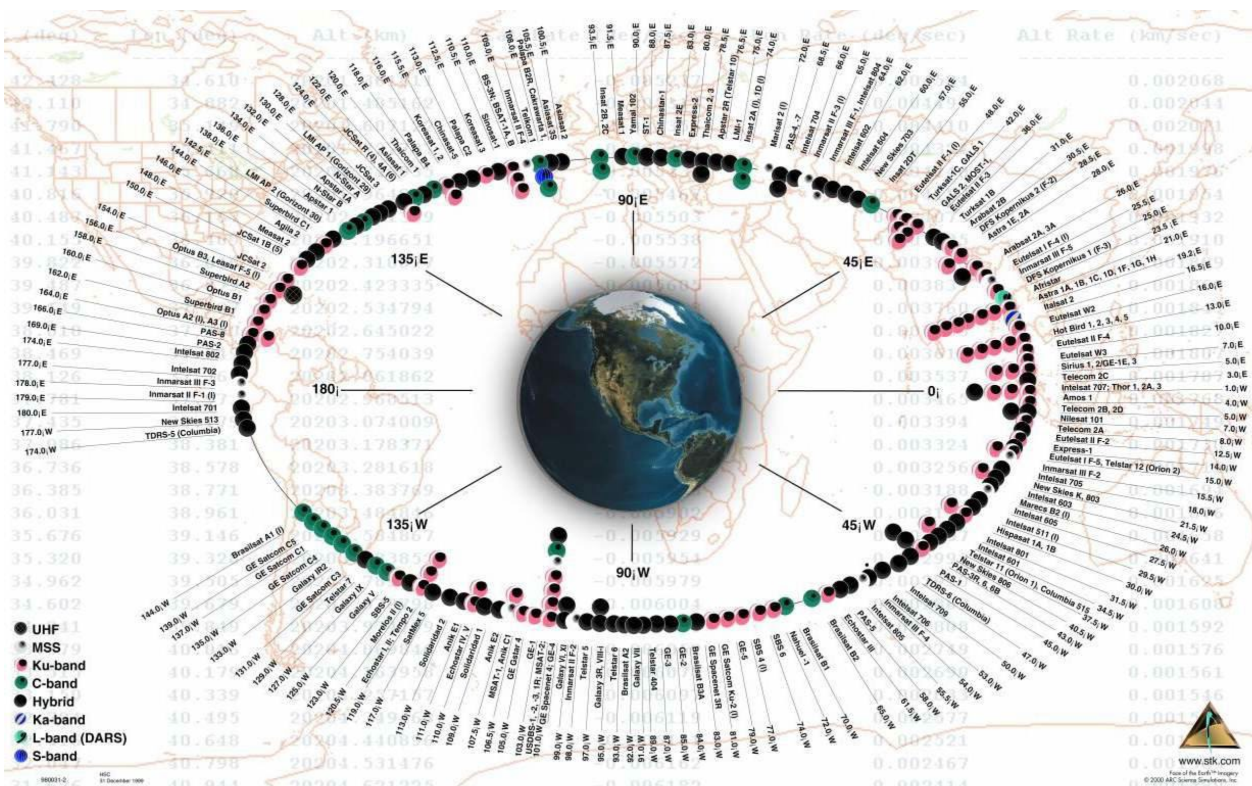
  - Orbital Saturation



Orbits

Types of Orbits. Geostationary Orbits GEO

- Disadvantages:
  - Satellite Eclipse
  - Delay
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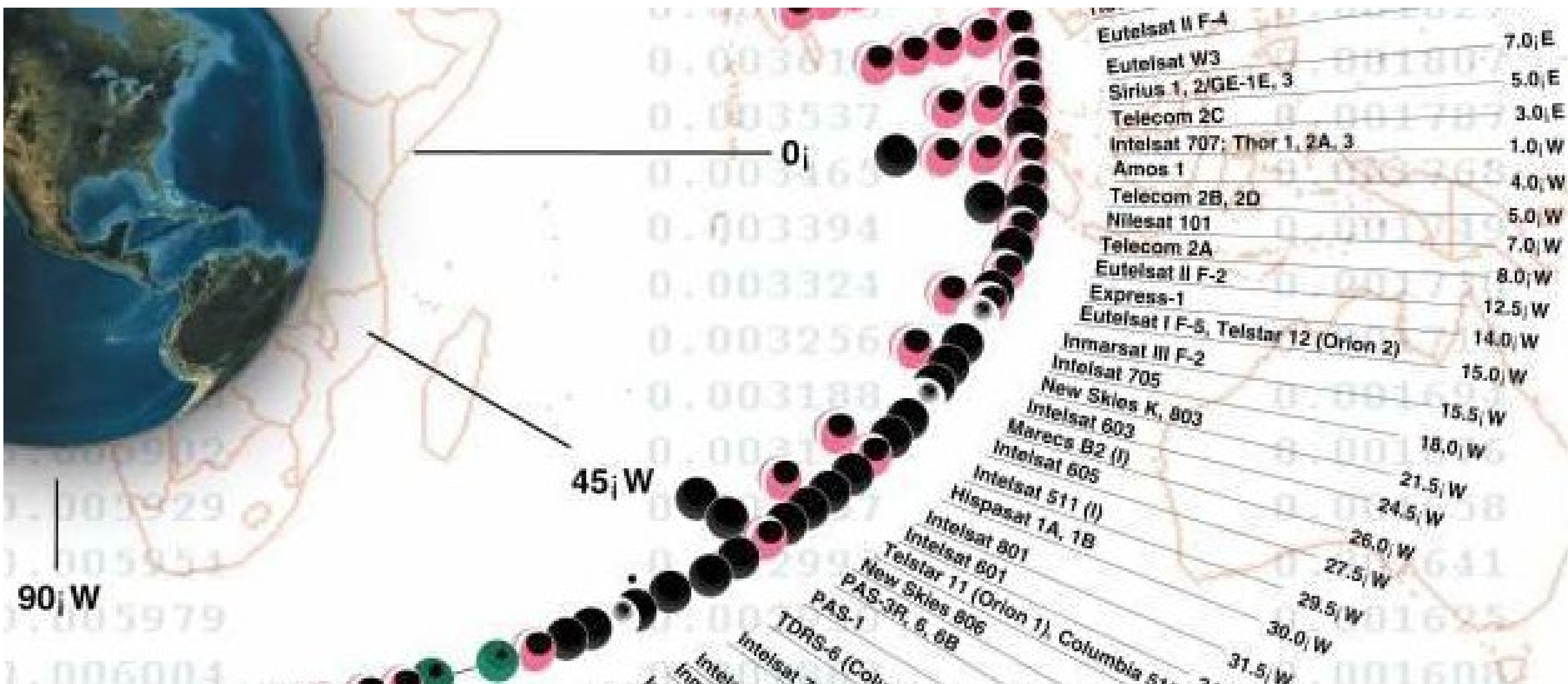


Orbits

Types of Orbits. Geostationary Orbits GEO

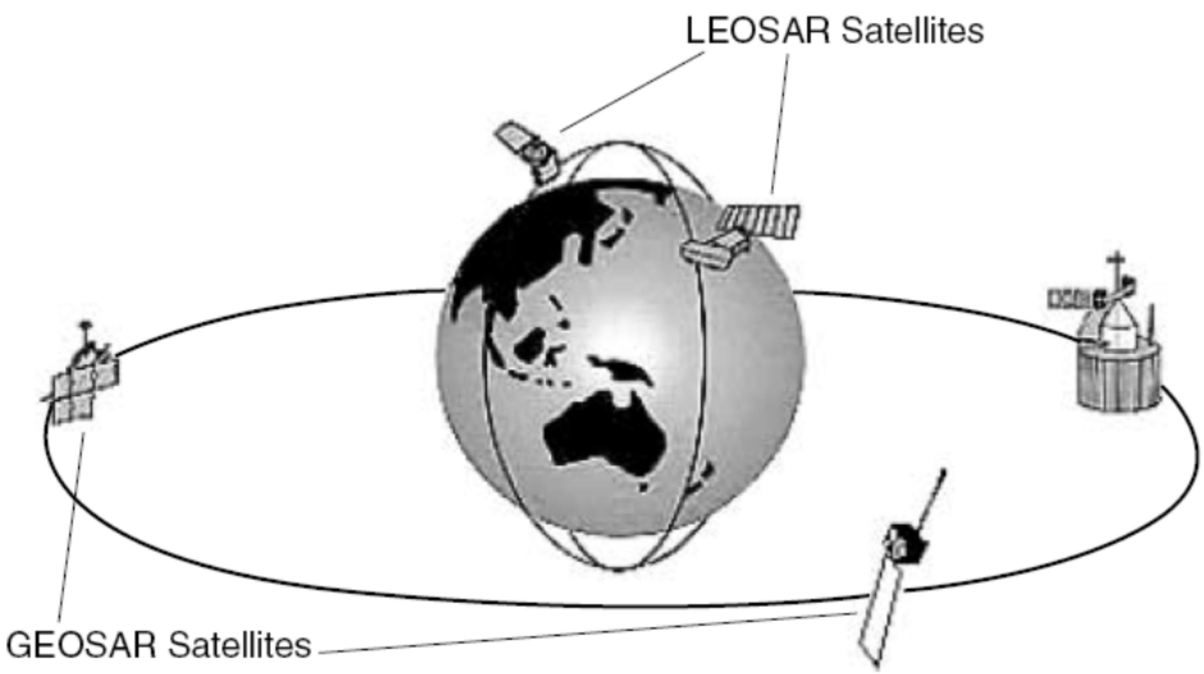
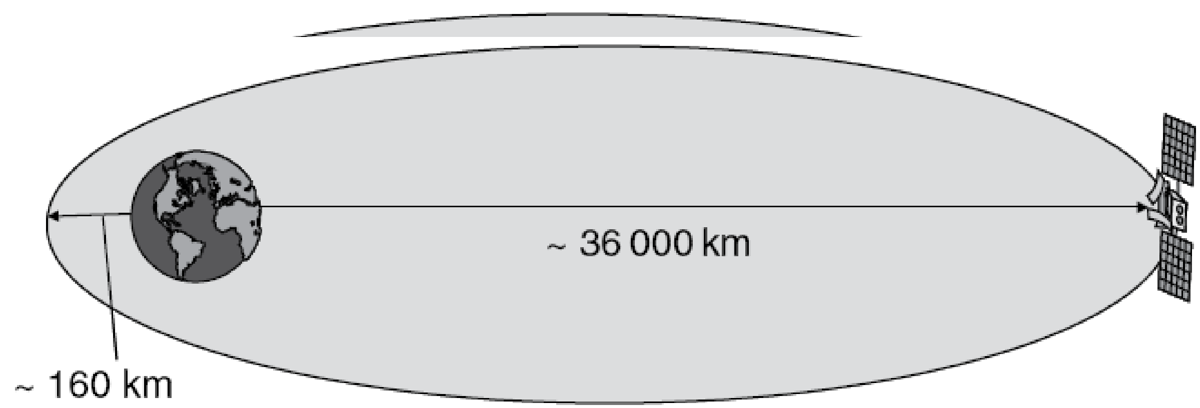


Figure 1.7 Geostationary Orbit Search and Rescue (GEOSAR) and Low Earth Orbit Search and Rescue (LEOSAR) satellites. (*Courtesy Cospas-Sarsat Secretariat.*)

Orbits

Types of Orbits. Highly Elliptical Orbit (HEO)

- Orbits with high e(0.77)
- The most popular Molniya:
  - Coverage at high latitudes> 70 °
  - Orbits 12 hours



- popular for high latitude or polar coverage
- often referred to as the 'MOLNIYA' orbit
- 8 to 10 hours of 12 hour HEO orbit available for communications from earth terminal, with 'GSO like' operations

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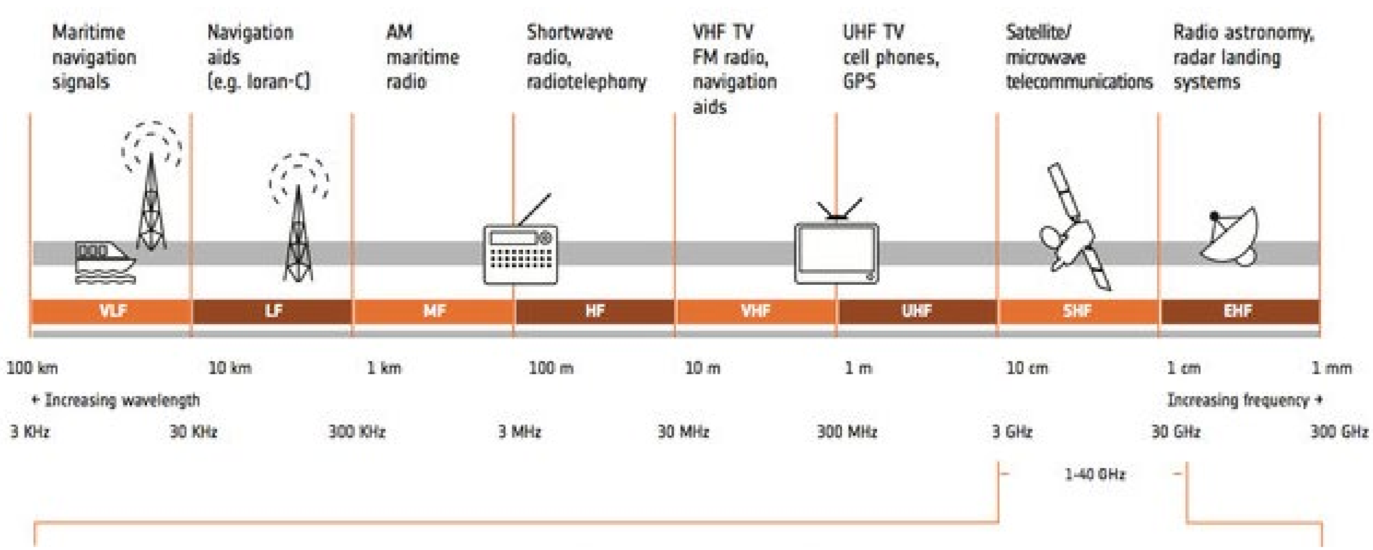
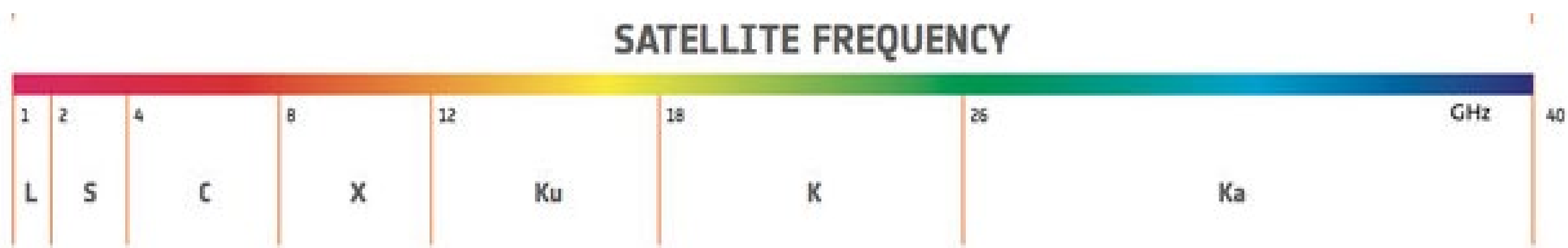
Satellite Frequency Bands

- Satellite technology is developing fast, and the applications for satellite technology are increasing all the time.
- The higher frequency bands typically give access to wider bandwidths, but are also more susceptible to signal degradation due to ‘rain fade’ (the absorption of radio signals by atmospheric rain, snow or ice).
- Because of satellites’ increased use, number and size, congestion has become a serious issue in the lower frequency bands. New technologies are being investigated so that higher bands can be used.



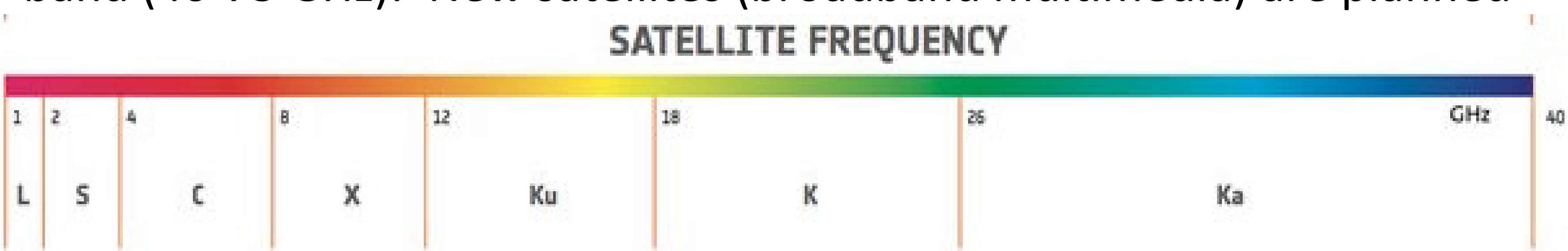
Satellite Frequency Bands

- L-band (1–2 GHz): Global Positioning System (GPS) carriers and also satellite mobile phones, such as Iridium; Inmarsat providing communications at sea, land and air; WorldSpace satellite radio.
- S-band (2–4 GHz): Weather radar, surface ship radar, and some communications satellites, especially those of NASA for communication with ISS and Space Shuttle. In May 2009, Inmarsat and Solaris mobile (a joint venture between Eutelsat and Astra) were awarded each a 2×15 MHz portion of the S-band by the European Commission.
- C-band (4–8 GHz): Primarily used for satellite communications, for full-time satellite TV networks or raw satellite feeds. Commonly used in areas that are subject to tropical rainfall, since it is less susceptible to rainfade than Ku band (the original Telstar satellite had a transponder operating in this band, used to relay the first live transatlantic TV signal in 1962).



Satellite Frequency Bands

- X-band (8–12 GHz): Primarily used by the military. Used in radar applications including continuous-wave, pulsed, single-polarisation, dual- polarisation, synthetic aperture radar and phased arrays. X-band radar frequency sub-bands are used in civil, military and government institutions for weather monitoring, air traffic control, maritime vessel traffic control, defence tracking and vehicle speed detection for law enforcement.
- Ku-band (12–18 GHz): Used for satellite communications. In Europe, Ku-band downlink is used from 10.7 GHz to 12.75 GHz for direct broadcast satellite services, such as Astra.
- Ka-band (26–40 GHz): Communications satellites, uplink in either the 27.5 GHz and 31 GHz bands, and high-resolution, close-range targeting radars on military aircraft.
- V-band (40-75 GHz): New satellites (broadband multimedia) are planned



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Satellite Subsystems

Satellites have two principal subsystems: The platform and the payload

- Platform: The platform is the basic frame of the satellite and the components which allow it to function in space, regardless of the satellite's mission. The platform consists of the following components:
  - Structure of the satellite: holds all of the components together as an integral unit and provides the interface with the launch vehicle. Must be strong enough to withstand the rigors of launch yet light enough to not unduly restrict payload weight.
  - Power: There are three types of energy sources: Solar, Chemical or Nuclear Energy
  - Propulsion: Used to achieve initial orbit and to make major position changes.
  - Stabilization and Attitude Control: Thermal Control
  - Thermal and Environmental Control
  - Telemetry, Tracking and Command

Satellite Subsystems

Satellite Payload

- The function and capabilities of the payload are the reasons a satellite is placed in orbit. The payload provides spacebased capabilities to the users. The payload distinguishes one type of satellite from another.
- Communications satellite: communications equipment that provides the relay link between the up- and downlinks from the ground.

- Communications payload: :
  - Antennas:
    - Reception
    - Transmission
  - Transponder:
    - Reception
    - Amplification
    - Frequency conversion
    - Transmission

Satellite Subsystems

Satellite Payload: Transponder

- Transponders are the payload of communication satellites.
- Reception of signal from reception antenna, amplification, frequency conversion, and transmission to transmitter antenna.
- Several transponders in one satellite. The frequency band is divided in slots. Each transponder works in one slot.
- For example C-band (500MHz) -> 12 transponders, 36 MHz bandwidth, 4 MHz guard bands.
- The frequency bands can be reused by polarization multiplexing:
  - Linear-> vertical / horizontal
  - Circular-> Right hand and left hand.
- and spatial separation
- Normal modern satellite: 24-48 transponders, C-band, Ku-band, or Ka-bands.

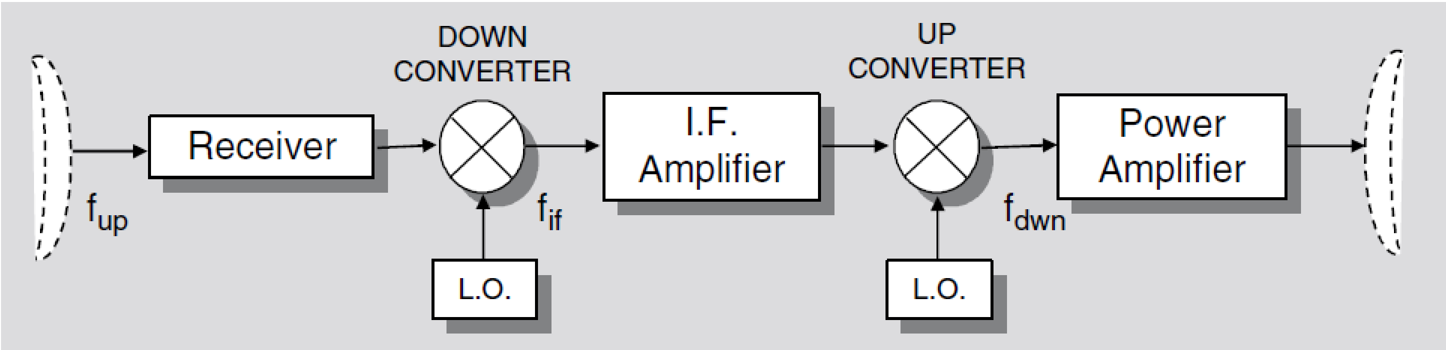
Satellite Subsystems

Satellite Payload: Transponder

Satellite Subsystems

Satellite Payload: Transponder: Frequency translation transponder

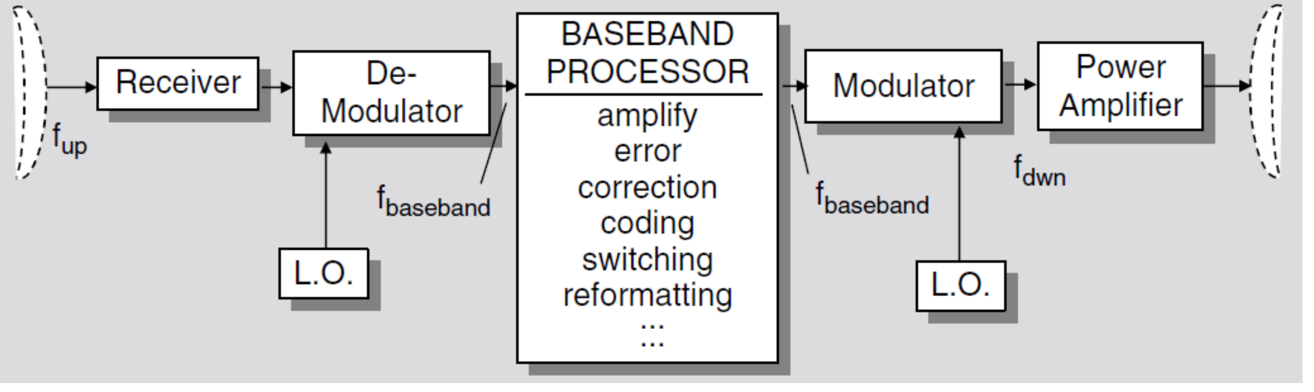
- Received signal is amplified and re-transmitted at different frequency.
- Signal degradation is accumulative.
- Unique alternative for analog signals.
- Transponder can be used for different services.



Satellite Subsystems

Satellite Payload: Transponder: On-board Processing transponder

- Received signal is demodulated, error corrected, modulated again and transmitted at different frequency (normally).
- Uplink and downlink signal quality are independent.
- Uplink and downlink modulation could not be the same.
- Transponder adapted to the service.
- More complicated design.
- Better performance.



Satellite Subsystems

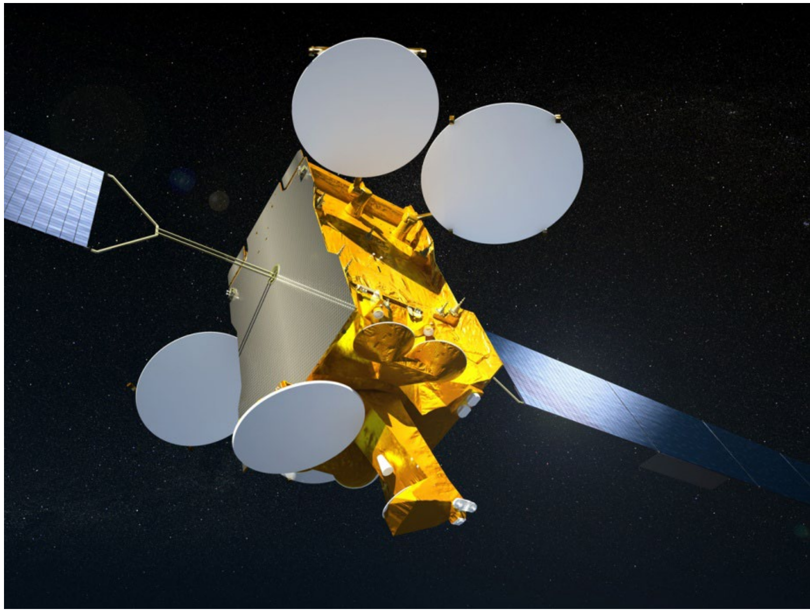
Satellite Payload: Power amplifiers

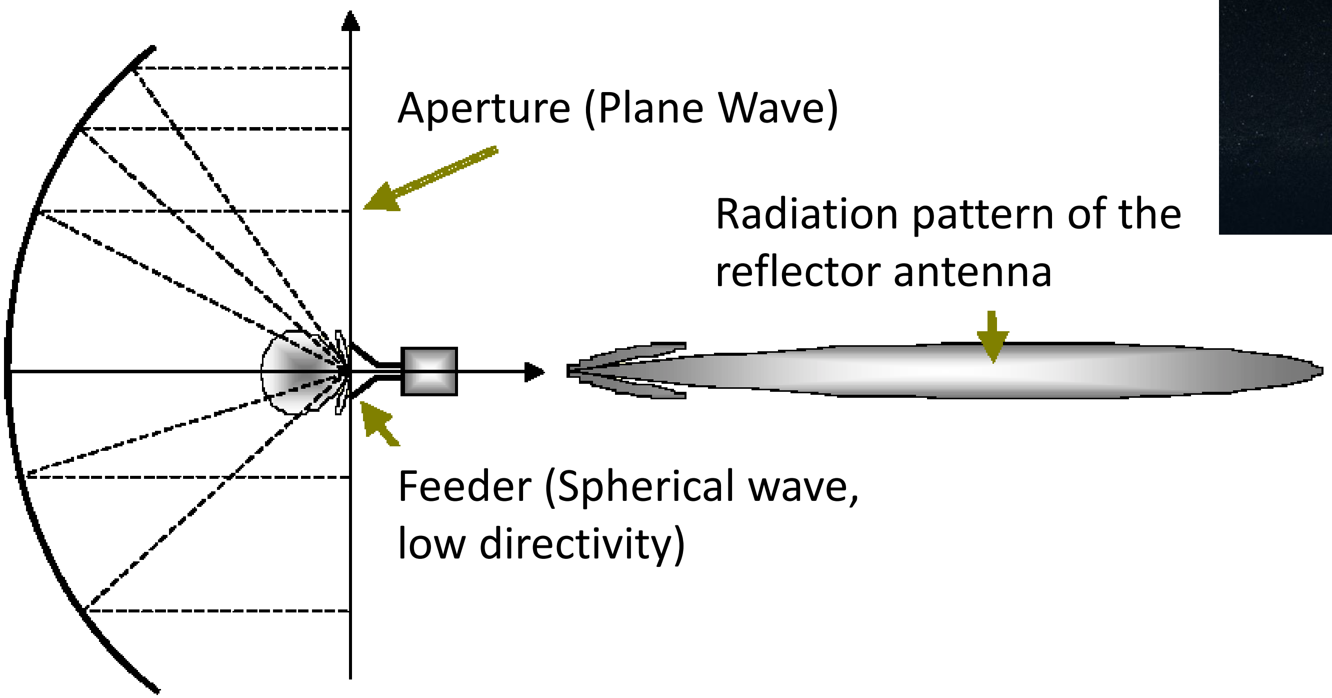
Satellite Subsystems

Satellite Payload: Antennas

Satellite Subsystems

Satellite Payload: Antennas: Parabolic reflector antenna





Satellite Subsystems

Satellite Payload: Antennas: Parabolic reflector antenna

- Parabolic reflector antenna
  - Frequency >8 GHZ
  - Gains of 25 dB and higher, beam widths of 1° or less.
  - Effective aperture (and D) is proportional to the physical area. Bigger antenna, larger D.

$$A_{eff} = S \cdot e = \pi \cdot r^2 \cdot e$$

$$D = \frac{4\pi \cdot A_{eff}}{\lambda^2} = 4 \cdot \left(\frac{\pi \cdot r}{\lambda}\right)^2 \cdot e$$

e, η_A: Efficiency, (0.5-0.9) normal value 0.65

Attention: Here, r is antenna radius, not distance from Tx to Rx

$$G(dB) \approx D(dB) = 26.4 + 10 \cdot \log(e) + 20 \cdot \log r(m) + 20 \cdot \log f(GHz)$$

Example: f =6 GHz, Radius r=2 m, efficiency e=0,55 **G = 39,4dB**

  - Feeder blocks waves. Efficiency lost.
  - Offset reflector solves this issue

Satellite Subsystems

Satellite Payload: Antennas: Parabolic reflector antenna

Table of Contents

Link Design Quality Parameters

The design parameters of link are parameters that combine the energy balance and system noise, to define the entire design link:

- C/N (carrier to noise ratio)
- C/N_o(Carrier to noise density ratio) C/(N/BW)
- Eb/N_o (Energy per bit to noise density ratio)

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Link Design Quality Parameters

- C/N_o(Carrier to noise density ratio)
  - This is the same concept as (C/N), but depending on the power density of noise instead of the noise power:

$$\left(\frac{c}{n}\right) = \left(\frac{c}{n_o}\right)\frac{1}{b_N}$$

  - In logarithmic scale:

$$\left(\frac{C}{N}\right) = \left(\frac{C}{N_o}\right) - B_N \text{ (dB)}$$

$$\left(\frac{C}{N_o}\right) = \left(\frac{C}{N}\right) + B_N \text{ (dBHz)}$$

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Link Design Quality Parameters

- E_b/N_o (Energy per bit to noise density ratio)
  - In digital communications, it is more useful to describe the link quality using the energy per bit than per the carrier power

$$e_b = c\, T_b$$

where c is the carrier power and Tb is the duration of a bit (seconds)

  - Link quality :

$$\left(\frac{e_b}{n_0}\right) = T_b\left(\frac{c}{n_0}\right) = \frac{1}{R_b}\left(\frac{c}{n_0}\right)$$

$$\left(\frac{e_b}{n_0}\right) = \frac{b_N}{R_b}\left(\frac{c}{n}\right)$$

where Rb is the bit rate (in bps)

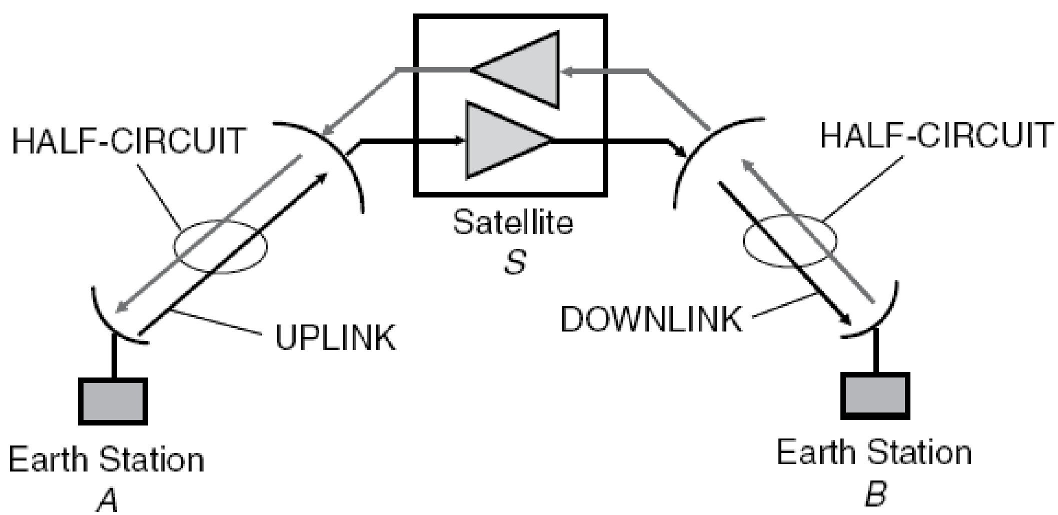
  - The higher this value is, the better link quality
  - Advantage: allows to compare the quality for different transmission rates

Composite Link Budget

General scheme of link

CALCULATIONS IN THREE STEPS: UP, DOWN AND TOTAL

(*not necessary in that order*)



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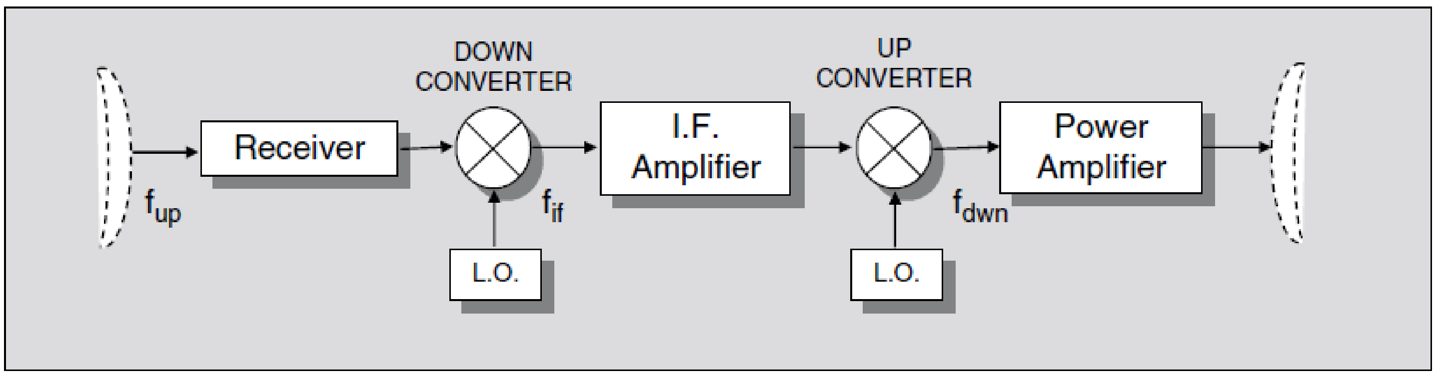
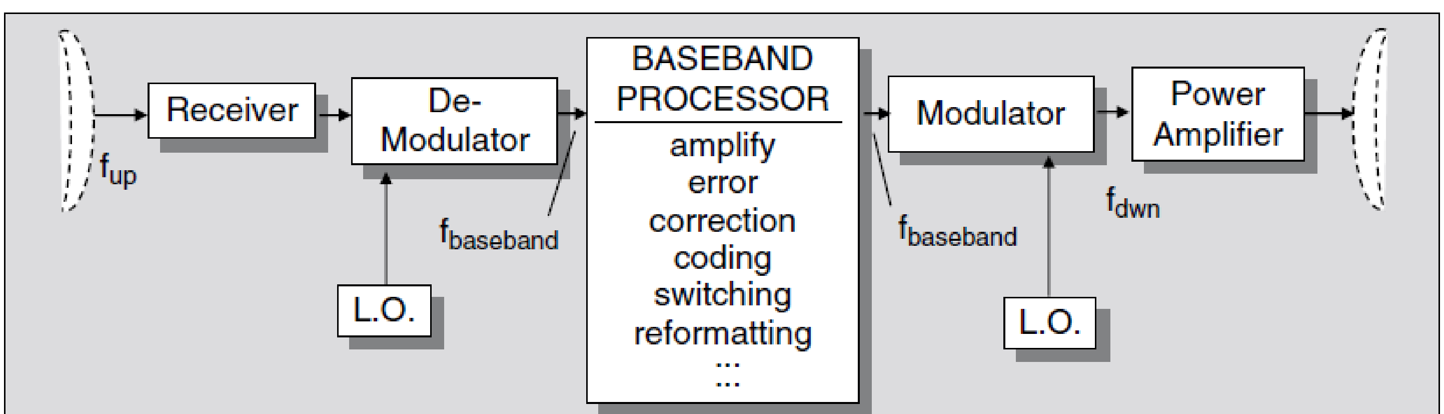
Composite Link Budget

General scheme of link

- Types transponder:
  - Frequency translation (FT) satellite: Amplification and frequency change

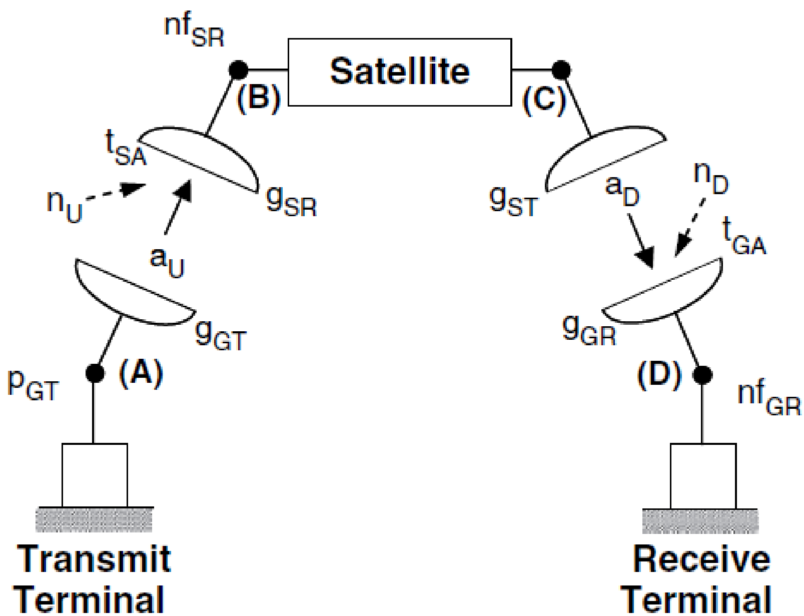


  - On-board processing satellite: also includes the regeneration of the signal. The links become independent



Composite Link Budget

General scheme of link



PARAMETER	UPLINK	DOWNLINK
Frequency (GHz)	f_U	f_D
Noise Bandwidth (MHz)	b_U	b_D
Data Rate (bps)	r_U	r_D
Transmitter Power (watts)	p_{GT}	p_{ST}
Transmit Antenna Gain	g_{GT}	g_{ST}
Free Space Path Loss	l_U	l_D
Path (Propagation) Loss (= $\Sigma\ell_i$)	a_U	a_D
Path Noise (Radio Noise)	n_U	n_D
Mean Atmospheric Temperature (K)	t_U	t_D
Receive Antenna Gain	g_{SR}	g_{GR}
Receiver Antenna Temperature (K)	t_{SA}	t_{GA}
Receiver Noise Figure	nf_{SR}	nf_{GR}

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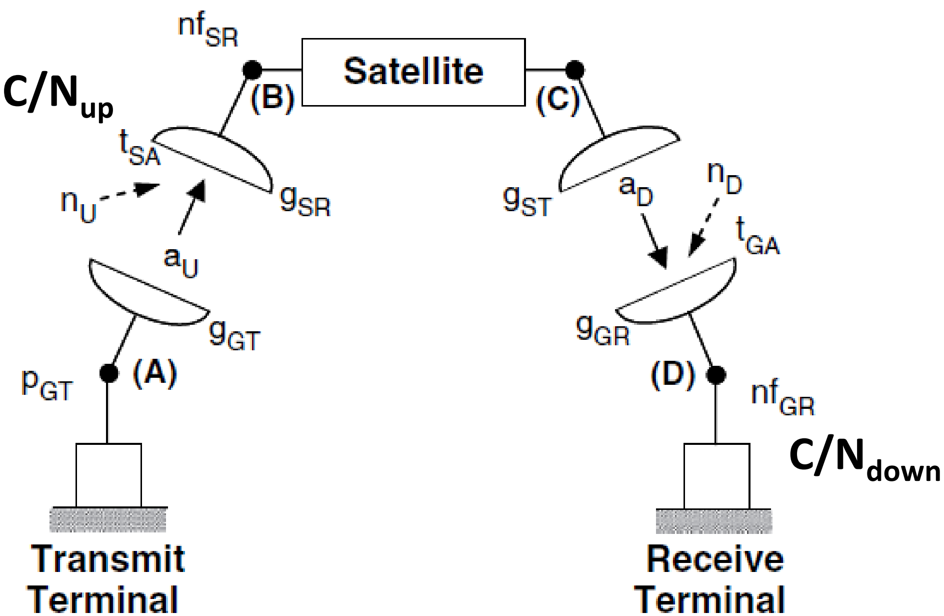
Composite Link Budget

Frequency translation (FT) Satellites



$$\left(\frac{c}{n}\right)_C^{-1}\Bigg|_{FT} \cong \left(\frac{c}{n}\right)_U^{-1} + \left(\frac{c}{n}\right)_D^{-1}$$

$$\left(\frac{c}{n_o}\right)_C^{-1}\Bigg|_{FT} \approx \left(\frac{c}{n_o}\right)_U^{-1} + \left(\frac{c}{n_o}\right)_D^{-1}$$

$$\left(\frac{e_b}{n_o}\right)_C^{-1}\Bigg|_{FT} \approx \left(\frac{e_b}{n_o}\right)_U^{-1} + \left(\frac{e_b}{n_o}\right)_D^{-1}$$

(C/N)_T < min((C/N)_up, (C/N)_down)

Erresistentzia paraleloen berdin. GOGORATU dB!!

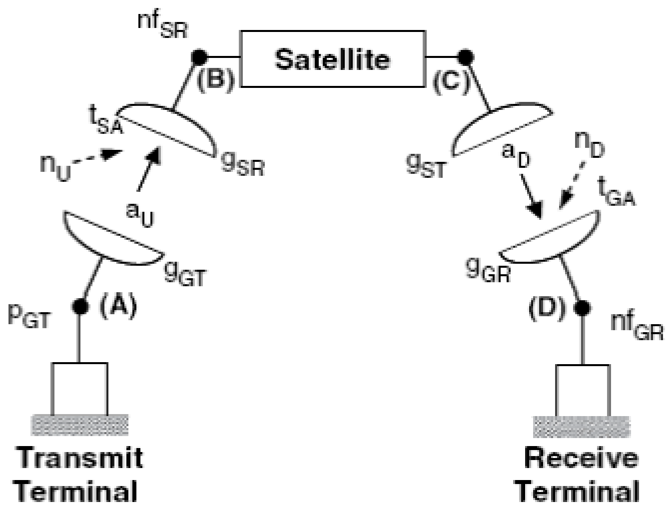
C/N_up = 30dB
C/N_down = 30dB

C/N_tot = 27dB

Composite Link Budget

G/T: Receiver Merit FIgure: Antenaren (Hartzailearen) parametro bat.
LOGARITMIKOAN: G(dBi) - T(dB)
G: Antenaren irabazia da.
T: Antenaren zarata tenperatura

Frequency translation (FT) Satellites



$$\left.\left(\frac{c}{n_o}\right)_C^{-1}\right|_{FT} \approx \left(\frac{c}{n_o}\right)_U^{-1} + \left(\frac{c}{n_o}\right)_D^{-1}$$

$$l_{fs} = \left(\frac{4\cdot\pi\cdot d}{\lambda}\right)^2$$

$$g = k\cdot\frac{4\cdot\pi\cdot S_g}{\lambda^2} = \frac{4\cdot\pi}{\lambda^2}\cdot S_e$$

- Downlink Link Budget

C/N_0= EIRP$_{SATELLITE}$ - L_{FS} - L_{Total} + G/T$_{Earth}$ - 10 log k

N = K·T·B

- Uplink Link Budget

C/N_0= EIRP - L_{FS}- L_{Total} + G /T$_{satellite}$ - 10 log k

G/T: Figure of merit of receiver

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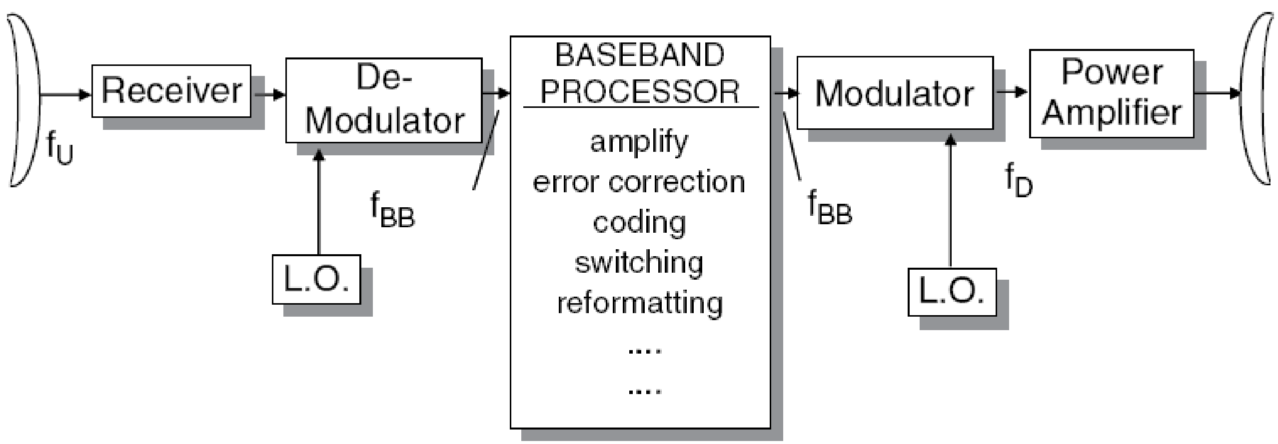
Composite Link Budget

On-Board Processing (OBP) Satellites

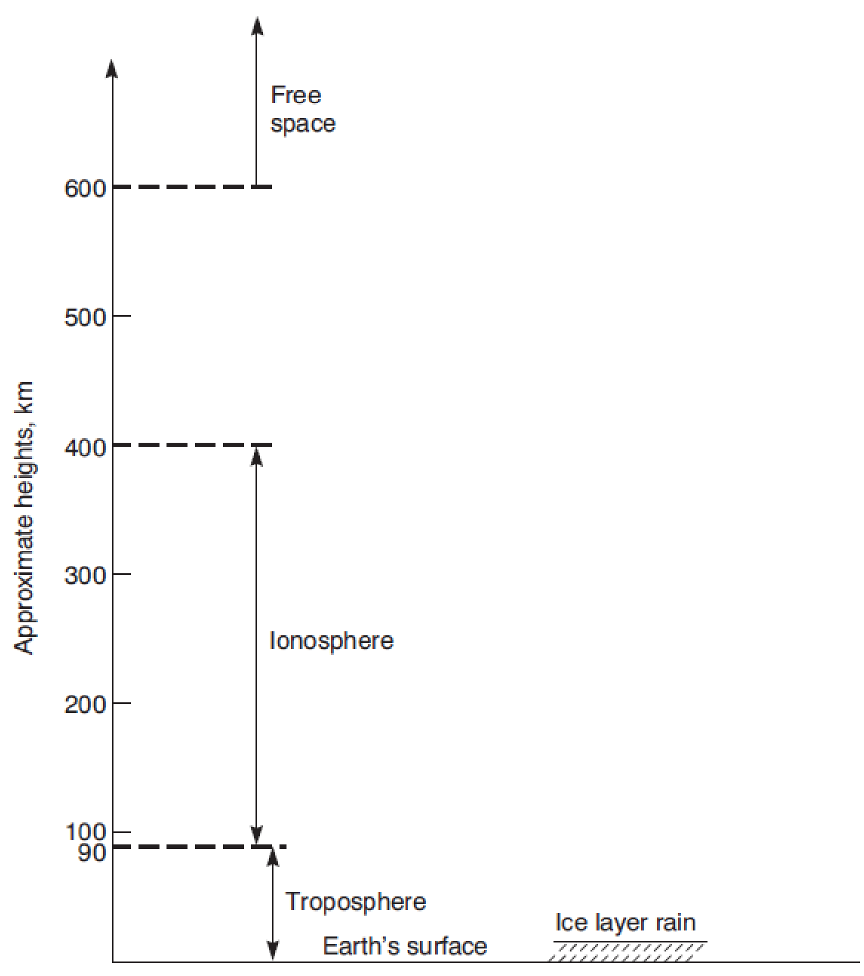
- The signal is amplified, corrected and regenerated
- The links are independent (noise is not cumulative)

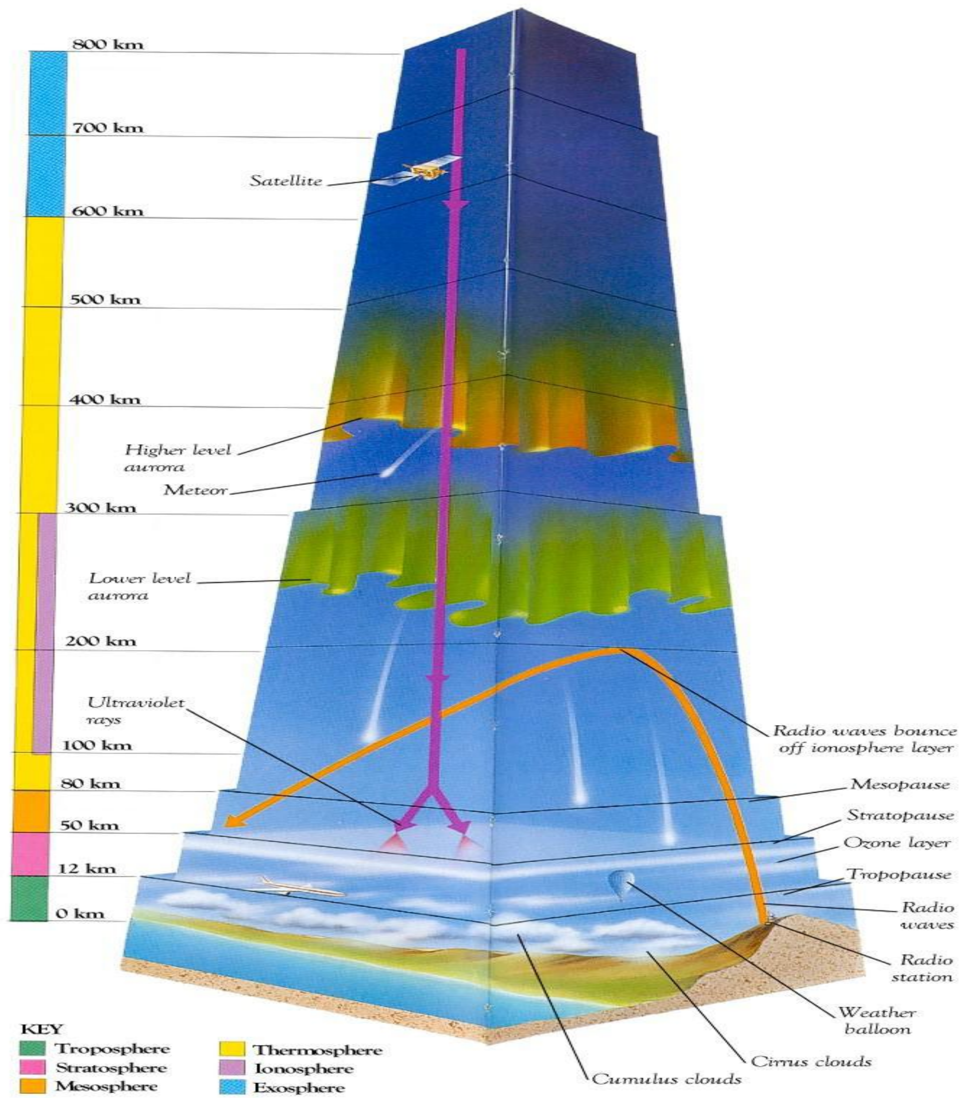


- The quality is evaluated using the probability of bit errors:
  - The link characterization (in the absence of errors correction on-board) is given by: $BER_{Total} = BER_{Uplink} + BER_{Downlink}$

Propagation mechanisms

Layers in the earth's atmosphere:

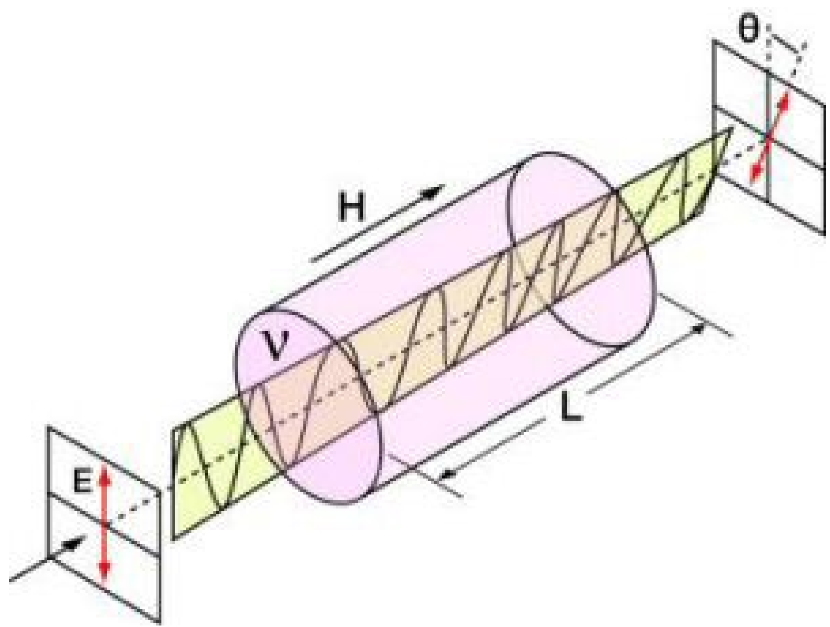




Propagation mechanisms

Ionospheric Effects:

- Ionospheric scintillations: are variations, which change with time, in the amplitude, phase, polarization, or angle of arrival of radio waves caused by irregularities in the ionosphere which has been ionized, mainly by solar radiation.
- Faraday rotation: is the rotation of the polarization plane of linear polarization of signal passing through a magnetized area in the ionosphere.



Propagation mechanisms

Troposferic Effects:

- The propagation loss on an Earth-space path, relative to the free-space loss, is the sum of different contributions as follows:
  - attenuation by atmospheric gases;
  - attenuation by rain, other precipitation and clouds;
  - focusing and defocusing;
  - scintillation and multipath effects;
  - attenuation by sand and dust storms.
- Each of these contributions has its own characteristics as a function of frequency, geographic location and elevation angle.
- As a rule, at elevation angles above 10°, only gaseous attenuation, rain and cloud attenuation and possibly scintillation will be significant, depending on propagation conditions.

Propagation mechanisms

As in fixed terrestrial radiolinks , it is necessary to include a fade margin in the link power-budget calculations to allow for simultaneous components of propagation losses.

Different approach based on the frequency for total additional losses:

- F <3 GHz variations that do not affect the median value: design criteria fundamentally
- F> 3 GHz vary considerably by rain and gases