Satellite fixed links

Electromagnetics
and
Remote Sensing Lab
(ERSLab)

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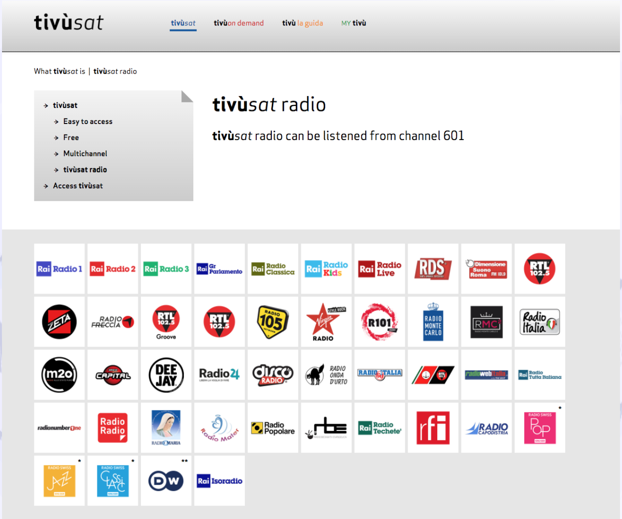
Outline

What they are

- A communication satellite is a microwave repeater station orbiting around the Earth.
- It is used for TLC, radio and television communications.
- The first communication satellite with radio TX was launched in 1957-
- There are more that 750 Earth-orbiting satellites, most of them for TLC.

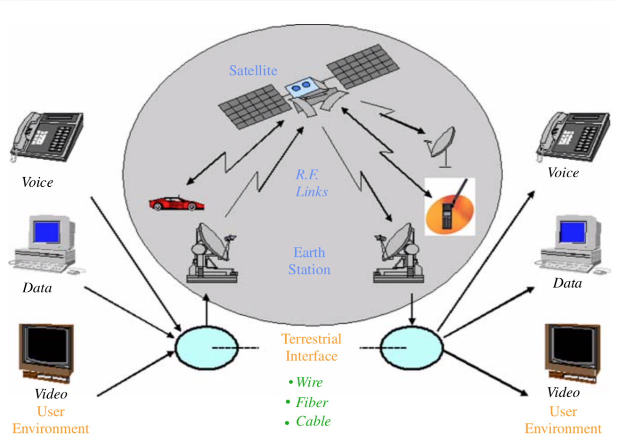
What they are: tv and radio broadcasting



What they are

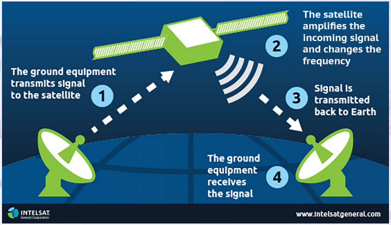
- When you listen to the radio, it is very likely that the signal you are receiving has been distributed from the central studios by satellite.
- Many newspapers and magazines are produced locally but printed centrally. The content of the paper is sent to the printing plants using satellite links.
- Even when a news or sports event shown on television is taking place just a few kilometers away from the studios, it has probably been transmitted via satellite.
- Most news agencies use satellites to distribute text, audio and video to their affiliate.
- In many countries, access to the Internet is by satellite communication.

What they are: satellite communications



Why we do care

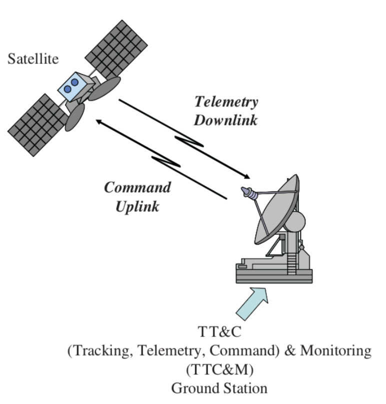
Two ground-based stations that are too far away to communicate directly (Earth bulge) can use a satellite as relay station to communicate.



- A TX Earth-based station TX the signal to the satellite (up-link).
- A RX Earth-based station RX the signal from the satellite (down-link).
- The satellite is equipped with a transponder that converts the signal coming from TX and sends is down to RX.

Satellite communications segments

The satellite communications portion is broken down into two areas or segments, the space segment and the ground (or earth) segment.

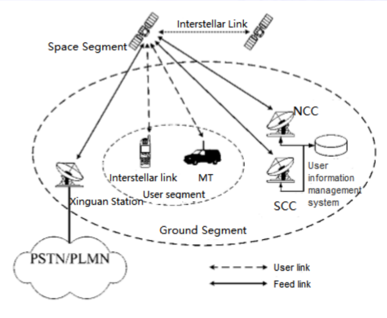


The space segment includes:

- The satellites the system consists of.
- The ground station that controls the satellites (TT&C).

Satellite communications segments

The satellite communications portion is broken down into two areas or segments, the space segment and the ground (or earth) segment.

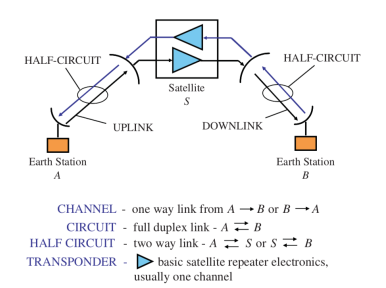


The ground segment includes:

- Fixed terminals (VSATs, domestic antennas).
- Transportable terminals (satellite news gathering (SGN) trucks).
- Mobile terminals.

Satellite links

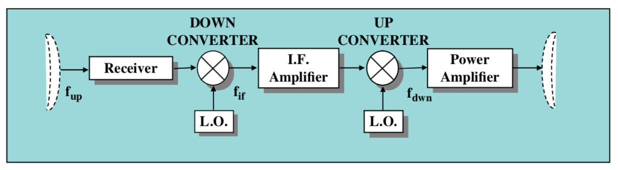
The satellite systems consists of two one-way air links between A and B. Either station has an uplink and a downlink.



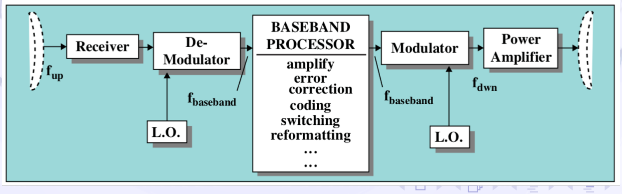
The electronic system (transponder) in the satellite receives the uplink signal, amplifies and possibly process the signal, then reformats the signal and transmit it back to the ground.

Trasponders

It provides the communication channel between the uplink and downlink signals. A typical communication satellite includes several transponders (aka channels).



Frequency Translation transponder



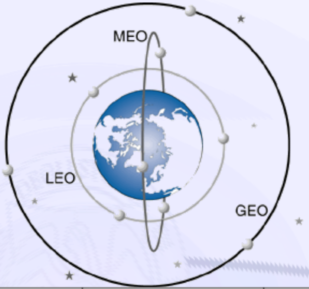
Regenerative Repeater

Advantages & disadvantages

Satellite communications bring the world to you anywhere and any time. . .

+ The area coverage is significantly larger than a terrestrial system.
+ Transmission cost of a satellite system is independent of the distance from the center of the coverage area.
+ Larger bandwidth are available.
- High costs for launching.
- There is a larger propagation delay (270ms @GEO vs 3μs terrestrial links)

Orbits and characteristics



Type	LEO	MEO	GEO
Description	Low Earth Orbit	Medium Earth Orbit	Geostationary Earth Orbit
Height	100-300 miles	6000-12000 miles	22,300 miles
Time in LOS	15 min	2-4 hrs	24 hrs
Merits	1.Lower launch costs 2.Very short round trip delays 3.Small path loss	1.Moderate launch cost 2.Small roundtrip delays	1.Covers 42.2% of the earth's surface 2.Constant view 3.No problems due to Doppler
Demerits	1.Short life 2.Encounters radiation belts 3.Short LOS	1.Round trip delays 2.Greater path loss	1.Larger round trip delays 2.Expensive equipment due to weak signal

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Path loss
Tropospheric effects
Rain attenuation
Empirical model - ITU
Gaseous absorption
Scintillation
Signal depolarization
Sky noise
Ionospheric effects
Ionospheric effects
Link budget
Examples
Direct Broadcasting Satellite
Deep space communication

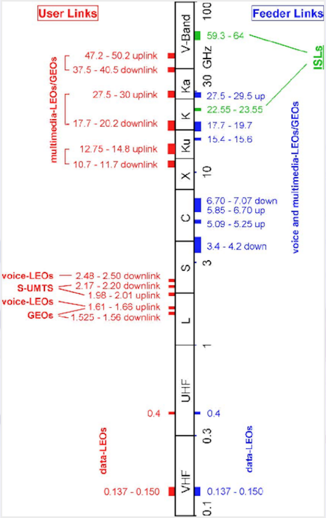
Orbits and characteristics

LEO: Typical Uses: Satellite phone, Military, Observation. LEO satellites complete one orbit roughly every 90 minutes at a height of between 160 and 600 km above the earth's surface.

MEO: Typical Uses: Weather Satellites, Observation, spy satellites. Any orbit that circles around the poles is referred to as a 'polar orbit'. Polar orbits have the advantage of covering a different section of the earth's surface as they circle the earth.

GEO: Typical Uses for satellites in Geostationary Orbits: Television satellites, Long Distance Communications satellites, Internet. Geostationary orbits allow these satellites to maintain their relative position over the earth's surface. Large ground-satellite-ground propagation times (225 ms round trip or more)

Satellite link channels



Uplink at frequency bands higher than downlink

Satellite link channels

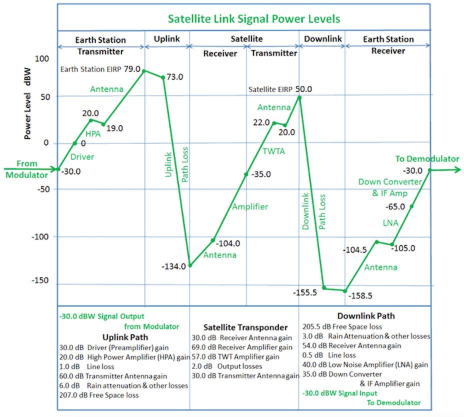
SATELLITE FREQUENCIES (Ghz)		
BAND	**DOWNLINK**	**UPLINK**
C	3.700 - 4.200	5.925 - 6.425
X (Military)	7.250 - 7.745	7.900 - 8.395
Ku (Europe)	FSS: 10.700 - 11.700 DBS: 11.700 - 12.500 Telecom: 12.500 - 12.750	FSS & Telecom: 14.000 - 14.800 DBS: 17.300 - 18.100
Ku (America)	FSS: 11.700 - 12.200 DBS: 12.200 - 12.700	FSS: 14.000 - 14.500 DBS: 17.300 - 17.800
Ka	~18 - ~31 GHz	
EHF	30 - 300	
V	36 - 51.4	

DBS = Direct Broadcast Satellite (Consumer direct-to-home Satellite TV)
FSS = Fixed Satellite Service (Geostationary Comms Satellites for TV/Radio stations and networks)

(Hz = Hertz, Mhz = Megahertz, Gh z= Gigahertz)

Satellite link budget

A significant loss of signal power can be attributed to free space loss by virtue of the vast distance between Earth stations and satellite.

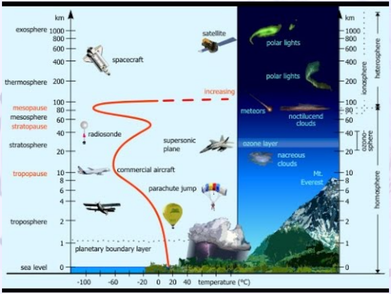


Satellite link budget

- The signal power radiated by the Earth station is about 30 dB (1000 times) greater than the signal power radiated by the satellite and the Earth station is able to receive weaker signals (and extract them from the noise) with levels of more than 20 dB (100 times) lower than the satellite can handle.
- The ground station transmitting antenna gain is different from the receiving antenna gain even though this is the same antenna. This is because the uplink frequency is higher than the downlink frequency.
- By contrast the satellite transmitter and receiver antennas have the same gain. This is because they use different antennas.

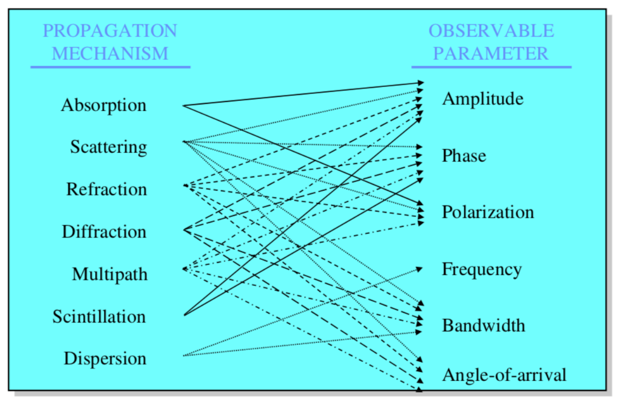
L_{ex}

L_{ex} is mainly determined by phenomena originating in the troposphere and the ionosphere.

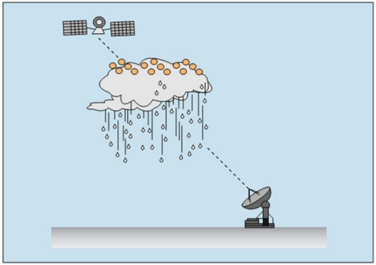


- Ionospheric effects: they influence systems operating below 3GHz.
- Tropospheric effects: they influence systems operating above 3GHz.

Radiowave propagation mechanisms and their impact on the parameters of a communication signal



Tropospheric effects

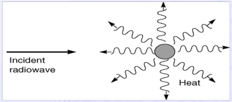


- Hydrometeor effects.
- Gaseous absorption.
- Refraction.
- Scintillation.
- Depolarization.
- Sky noise.

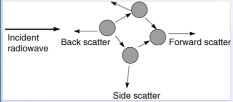
Outline

Path loss due to hydrometeor effects

When propagating through rain, snow, hail, or ice droplets, radiowaves suffer from power loss due to hydrometeor scattering and absorption.



- It arises from the conversion of em energy into heat within an attenuating particle.
- It is the dominant phenomenon causing power loss between 10GHz and 30GHz.



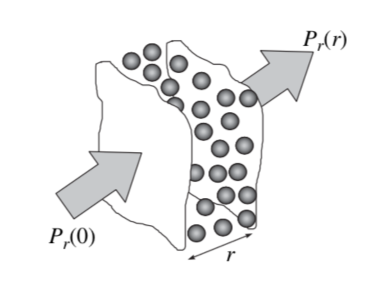
- It arises from redirection of em waves into various directions; hence only a fraction of the total energy reaches the receiver.
- It is the major limiting factor in the EHF band (>30GHz).

The combined effect of hydrometeor scattering and absorption results in a power loss proportional in dB to the square of the frequency.

Path loss due to precipitation

Among hydrometeor effects, rain is the key effect to determine system reliability.

- From a physical viewpoint, the path loss due to rain increases with the number of raindrops along the path, their size and the length of the path.



Path loss due to precipitation

- Assuming constant density and shape, the received power is expected to reduce exponentially with the distance r along the rainy path:

$$P_R = P_R(0)e^{-\alpha r}, \tag{1}$$

- α is the reciprocal of the distance where the power reduces about 37%. It depends on the drop distribution $N(D)$ and the drop cross-section $C(D)$:

$$\alpha = \int_{D=0}^{\infty} N(D)C(D)dD \tag{2}$$

Path loss due to precipitation

Path loss due to rain attenuation

L_{ex} due to rain is given by:

$$L_{rain} = 10 \log \frac{P_T}{P_R} = 4.343 \alpha r \quad (3)$$

It is usual to define the specific rain attenuation (dB/km) as:

$$\gamma = \frac{L}{r} = 4.343 \alpha \quad (4)$$

- Typically $N(D)$ is approximated using an exponential distribution:

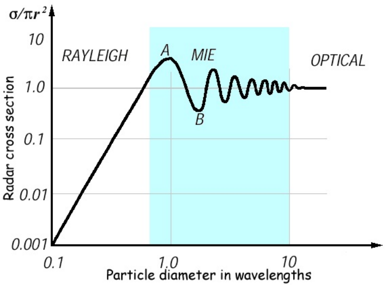
$$N(D) = N_o e^{-\frac{D}{D_m}} \quad (5)$$

where N_o and D_m are two parameters, with D_m depending on the rain rate R (mm/h).

Path loss due to precipitation

The attenuation cross-section $C(D)$ is investigated assuming a spherical raindrop illuminated by a plane wave.

T



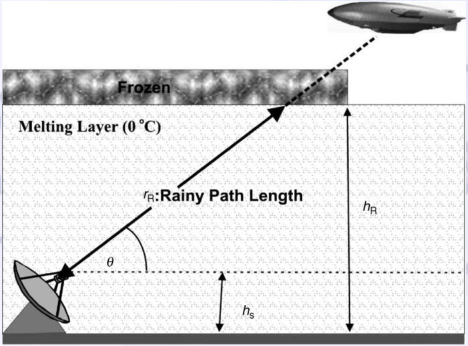
- A low freq., i.e.; the drop size is smaller that the wavelength (Rayleigh scattering). The dominant attenuation effect is absorption.
- A higher freq., i.e.; the drop size is comparable to the the wavelength (Mie scattering). The dominant attenuation effect becomes scattering.

In practical cases, empirical path loss models are adopted.

Outline

Geometry of the problem

Schematic presentation of an Earth-space path giving the parameters to be input into the attenuation prediction process



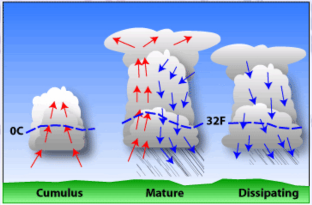
- r_r Rainy path length
- h_s Height of the Earth station
- h_r Effective rain height
- θ Elevation angle

Key steps to determine L_{rain}

1. Determine h_r (km) according to ITU recommendations. It is around 5km.
2. Evaluate r_r according to θ:
   - $\theta > 5°$

$$\frac{h_r - h_s}{sin\theta} \tag{6}$$

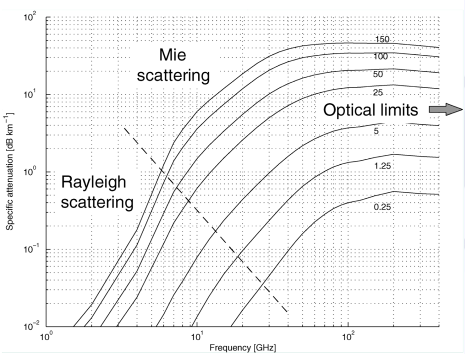
   - $\theta < 5°$ penalize r_r (6) by the horizontal rain factor s_r that accounts for the variation of the rain along with the horizontal direction.



Key steps to determine L_{rain}

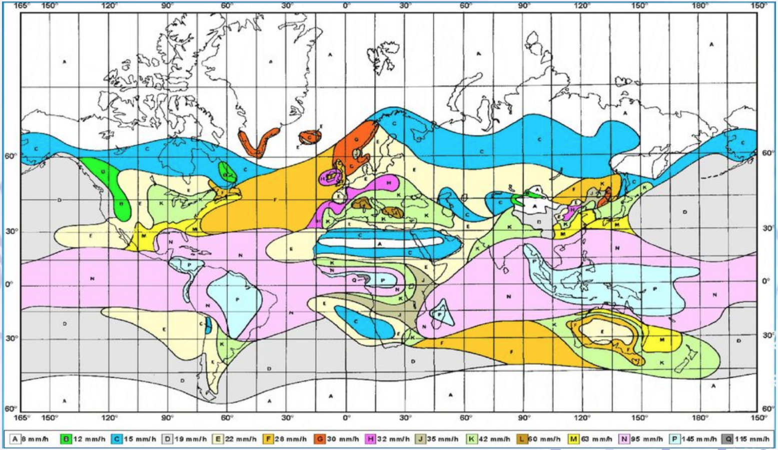
3. Obtain the rainfall rate of an average year R and the frequency dependent coefficients (a,b) according to ITU recommendations and evaluating the specific rain rate attenuation (dB/km) according to:

$$\gamma = aR^b s_r r_r \tag{7}$$



Rain regions

The 15 regions the world is split into according to precipitation intensity based on ITU



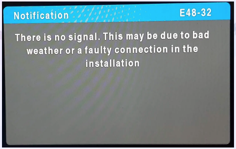
L_{rain} - Temporal variations

Rainfall rate

The period of time that leads to a rainfall rate exceeding a given value is what one really needs to design an operational satellite link

Light rain vs heavy storm

It worth recalling that frequent light rain will lead to less outage than the same amount of rain falling in occasional heavy storms!



Key steps to determine $L_{rain0.01}$

Why we do care

The path loss exceeded for 0.01% of time ($L_{rain0.01}$) is the way to account for temporal variations.

The specific rain rate attenuation (7) shall be modified as follows:

- Replacing R with the rainfall rate $R_{0.01}$ exceeded for 0.01% of an average year provided by ITU recommendations.
- Replacing s_r with the horizontal rain variation factor exceeded for 0.01% of an average year.

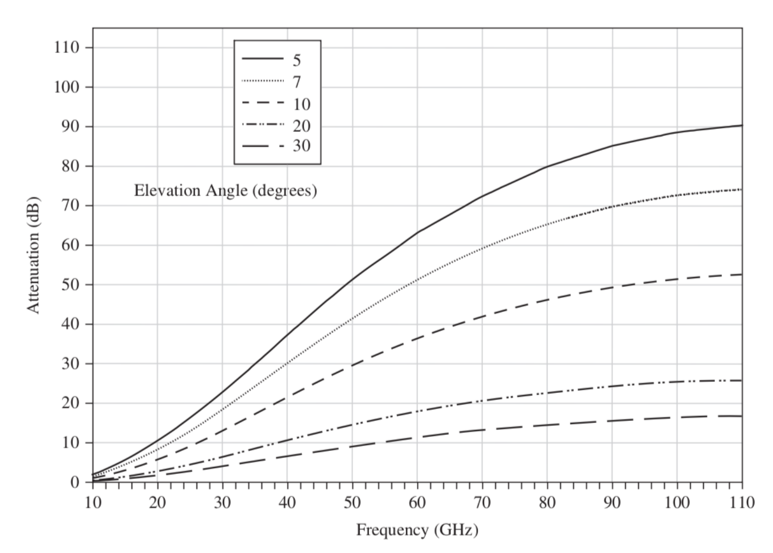
$L_{rain0.01}$

The rain path loss exceeded for 0.01%of an average year is given by:

$L_{rain0.01}$

$$L_{0.01} = aR_{0.01}^{b} s_{r0.01} r_r \tag{8}$$

L_{rain} as a function of frequency and elevation angle



L_{rain} as a function of %Availability

Assumptions

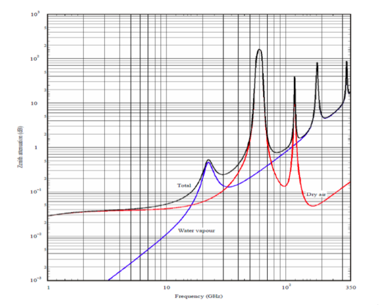
Rain region	D2
Elevation angle	40°
Earth station latitude	39°
Earth station altitude	0 km
Clear sky temperature	25 K
Receiver equivalent temperature	120 K
Rain temperature	300 K
Polarization	vertical

Availability (percent)		99.99	99.95	99.90	99.50	99.00	98.00	97.00
Unavailability (percent)		0.01	0.05	0.10	0.50	1.00	2.00	3.00
Maximum rain rate (mm/h)		47.1	22.3	15.2	5.3	3.0	1.5	0.9
Attenuation (dB)								
C-band downlink	4 GHz	0.2	0.1	0.1	0.0	0.0	0.0	0.0
C-band uplink	6 GHz	1.3	0.5	0.3	0.1	0.0	0.0	0.0
Ku-band downlink	12 GHz	10.5	4.5	2.9	0.8	0.4	0.2	0.1
Ku-band uplink	14 GHz	13.7	6.1	4.0	1.2	0.6	0.2	0.1
Ka-band downlink	20 GHz	26.4	12.2	8.1	2.5	1.3	0.6	0.3
Ka-band uplink	30 GHz	48.8	23.5	16.1	5.4	2.9	1.4	0.8
V-band downlink	40 GHz	68.8	34.6	24.2	8.6	4.9	2.4	1.5
V-band uplink	50 GHz	83.8	43.7	31.2	11.8	6.9	3.5	1.9
Decrease in G/T (dB)								
C-band downlink	4 GHz	0.4	0.2	0.1	0.0	0.0	0.0	0.0
Ku-band downlink	12 GHz	4.4	3.5	2.8	1.2	0.7	0.3	0.2
Ka-band downlink	20 GHz	4.6	4.4	4.2	2.6	1.8	0.9	0.6
V-band downlink	40 GHz	4.6	4.6	4.6	4.2	3.6	2.6	1.9

Outline

Absorption due to Oxygen and water

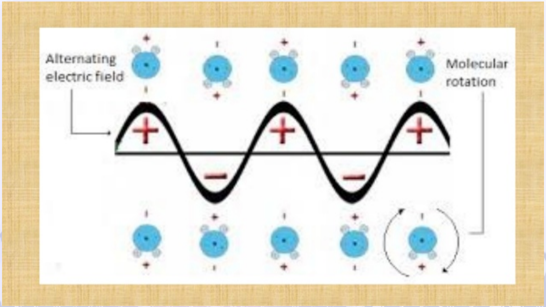
Gaseous absorption, mostly from oxygen and water vapor, contributes to the total attenuation of radiowaves, especially in the case of low elevation angles.



- It increases with frequency.
- There are several resonance peaks corresponding to different modes of vibration.
- The contribution of gaseous absorption to the total attenuation is small compared to the attenuation due to rain.

It results in an upper frequency limit to satellite communications.

Absorption due to clouds



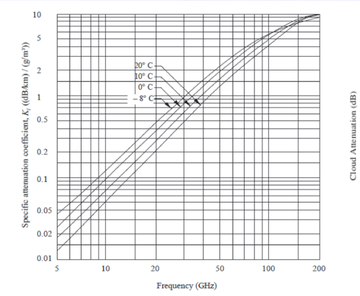
Water droplets

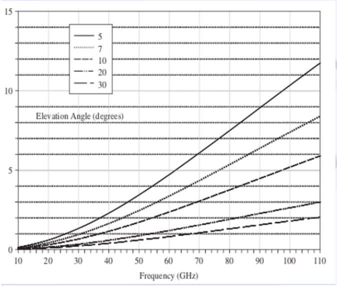
Clouds consist of small ($< 0.1 mm$) water droplets, not water vapor!

Absorption due to clouds

Rayleigh approximation

The small size of water droplets the clouds consist of allows using the Rayleigh approximation in the calculation of specific cloud's attenuation. It increases with frequency and with decreasing elevation angle.

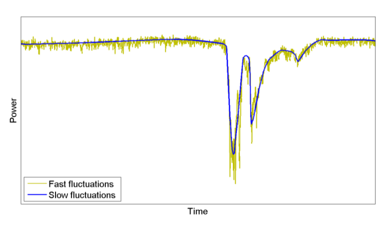




Outline

Tropospheric scintillation

Variations in the magnitude and the profile of the refractive index of the troposphere lead to a fast amplitude fluctuation of the received signal, known as scintillation.

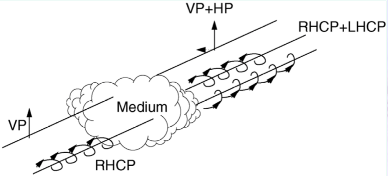


- Fluctuations increase with frequency and depend upon the length of the slant path.
- The distribution of the fluctuation (in dB) is approximately Gaussian.
- Scintillation effects reduce when using large antennas.

Outline

Signal depolarization

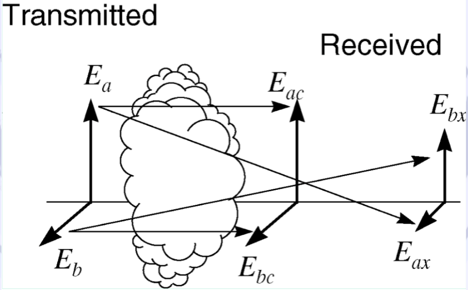
The polarization state of a wave passing through an anisotropic medium (rainy area with horizontal wind component) is altered.



- This phenomenon does not affect single polarized satellite systems.
- It affects systems reusing frequency by transmitting two orthogonal polarized signals.

Signal depolarization

When reusing frequency by transmitting two orthogonal polarized signals for optimum RF spectrum utilization, depolarization results in cross-polar interference, i.e. part of the transmitted power in one polarization interferes with the orthogonal polarized signal.



Depolarization is correlated with rain attenuation

XPD and XPI

The effects of depolarization can be quantified using:

- Cross-polar discrimination (XPD):

$$XPD = 20 \log \frac{E_{ac}}{E_{ax}} \tag{9}$$

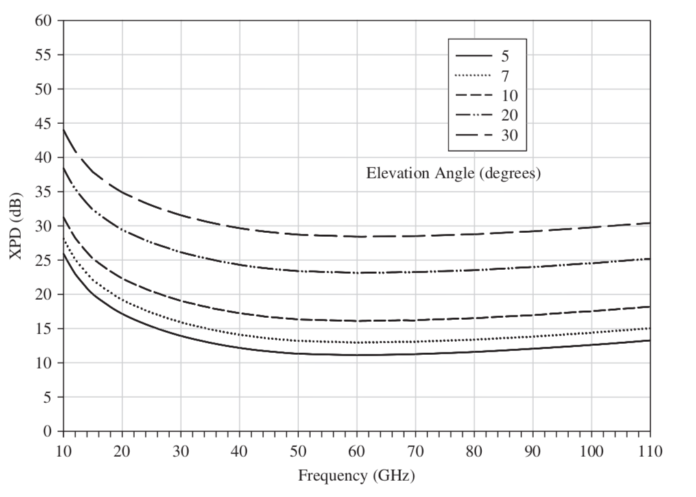
- Cross-polar isolation (XPI):

$$XPI = 20 \log \frac{E_{ac}}{E_{bx}} \tag{10}$$

What they measure

XPD measures how much of a signal in a given polarisation is scattered into the opposite polarisation by the medium alone. XPI measures how much two signals of opposite polarisations transmitted simultaneously will interfere with each other at the receiver.

XPD


60
55
50
45
40
35
30
25
20
15
10
5
0
XPD (dB)
10
20
30
40
50
60
70
80
90
100
110
Frequency (GHz)
5
7
10
20
30
Elevation Angle (degrees)

Outline

Sky noise

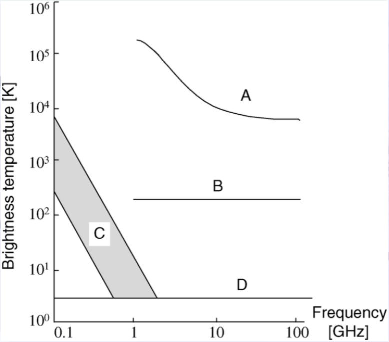
Elementary physics tells us that anything that absorbs electromagnetic energy radiates it as well. The energy radiated by the tropospheric absorbing media (oxygen, water vapor, rain drops, etc.) is incoherent and broadband.

Sky noise

It is received by the Earth station antenna along with the downlink signal, and appears at the receiver output as thermal noise - indistinguishable from the thermal noise generated in the receiver front end. The effect of the received noise energy is accounted for by adding a “sky noise” temperature to the Earth station receiver noise temperature.

Sky noise

Any natural absorbing medium in the atmosphere which interacts with a radiowave will not only produce a signal amplitude reduction (attenuation), but will also be a source of thermal noise power radiation.

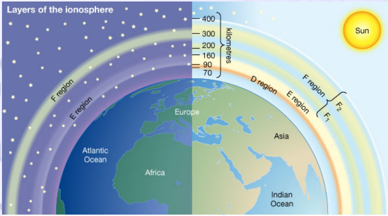


An effective noise temperature is evaluated that includes:

- A: Sun's noise.
- B: Moon's noise.
- C: Radio stars and nebula noise.
- D: Cosmic background noise.

Ionosphere

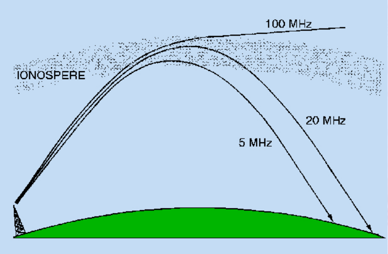
It is a region of ionized plasma which surrounds Earth at a distance ranging from around 50km up to 2000km.



- Ions may have come originally from either the solar wind or ionization of atmospheric particles by Sun's radiation.
- It separates into 4 distinct layers that call for different ions concentration.
- The size of these layers varies according to night and day-time.

Ionospheric refraction: high-pass filter

The plasma content of the ionosphere changes the effective refractive index that is encountered by em wave changing their direction by increasing wave velocity.



- The refraction process depends on wave frequency, elevation angle of ground-based antenna and electron/ion content.

Higher-frequencies

Em waves whose frequency is below the plasma frequency (10MHz) are totally reflected back to the Earth.

Outline

Effects on EM waves propagating through the atmosphere

ERSLab

F. Nunziata

frequency range ~30MHz – ~3GHz.

ionospheric effects depend on

Total Electron Content (TEC)

- Faraday rotation
- Group delay
- Dispersion

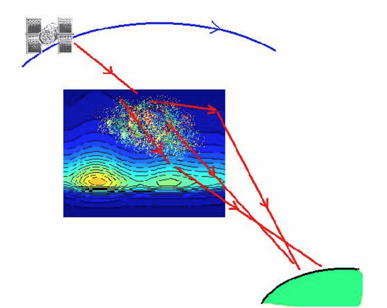
$\propto$ TEC

Inhomogeneities

- Scintillation

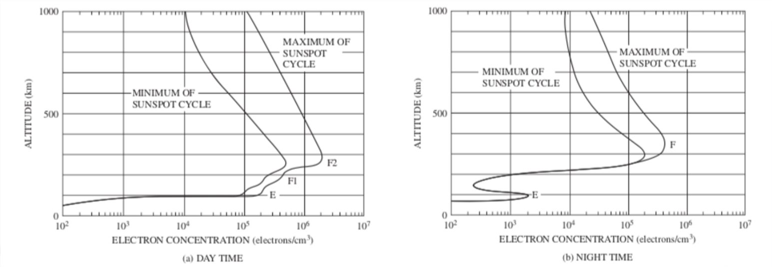
Scintillation

It consists of rapid fluctuations of the amplitude and phase of the radiowave caused by irregularities in the electron density.



- The main mechanism is forward scattering and diffraction.
- It is related to peak-to-peak fluctuations of the received intensity signal.

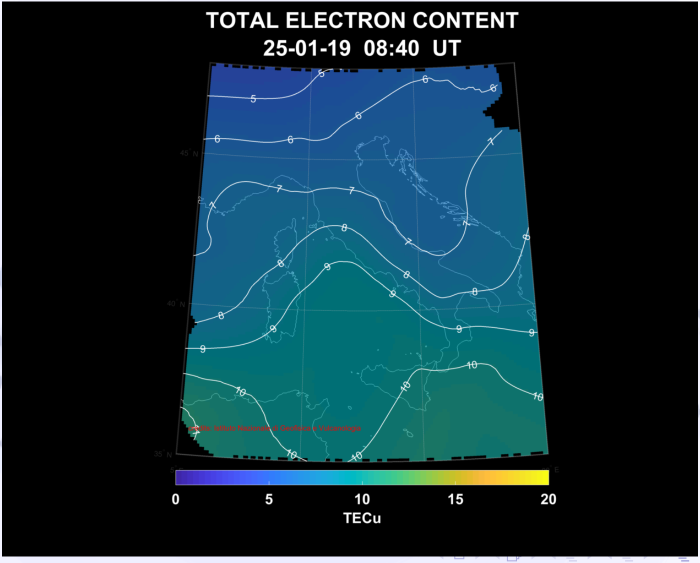
TEC



TEC

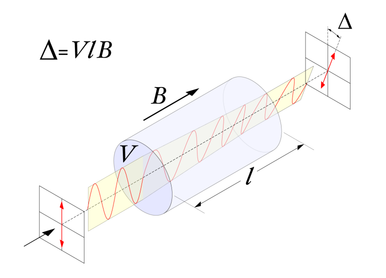
Most of the ionospheric impairments are directly related to TEC that varies according to geomagnetic latitude, diurnal cycle, yearly cycle, etc.

TEC


TOTAL ELECTRON CONTENT
25-01-19 08:40 UT
credits: Istituto Nazionale di Geofisica e Vulcanologia
0
5
10
15
20
TECu

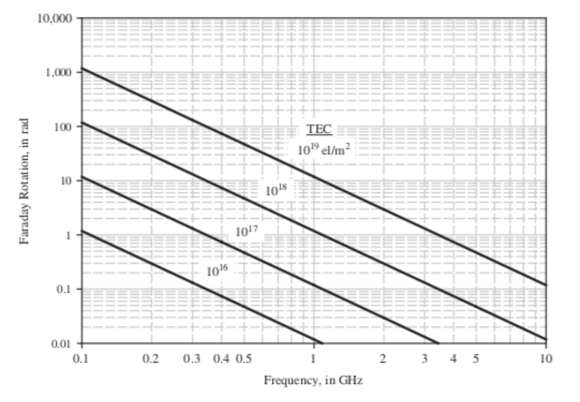
Faraday rotation

A linearly polarized plane wave becomes rotated when propagating through the ionosphere due to the joint effect of free electrons and Earth's magnetic field.



- Faraday effect diminishes rapidly with increasing frequency ($f^{-}2$).
- To minimize the extra path-loss deriving by polarization mismatch between antennas one can use circular polarization.

Faraday rotation

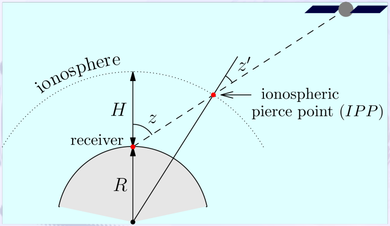


TEC

Most of the ionospheric impairments are directly related to TEC that varies according to geomagnetic latitude, diurnal cycle, yearly cycle, etc.

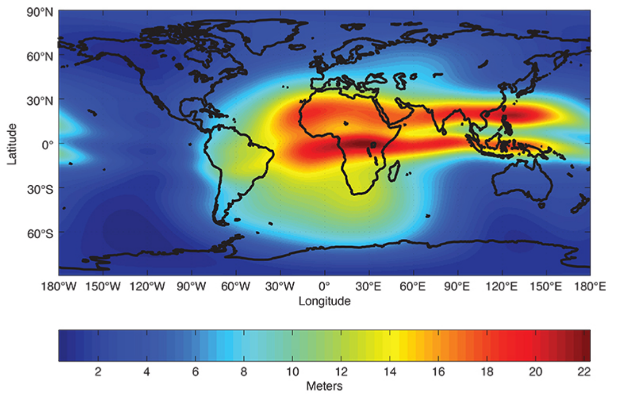
Propagation delay

It refers to the reduction of the velocity of the radiowave due to free electrons in the propagation path



- The travel time of the wave increases.
- It decreases with increasing frequency and decreasing TEC.
- It is a key issue for GNSS.

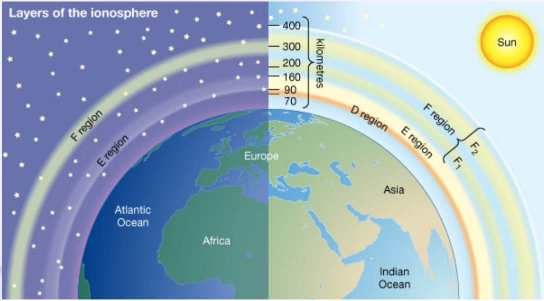
Propagation delay



Ionospheric correction

Ionospheric delay corrections for single-frequency Galileo users.

Dispersion

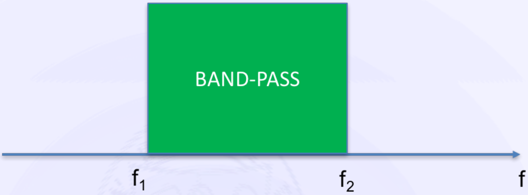


Dispersion

A wide bandwidth will be smeared in time when arriving at the receiver due to atmospheric refractivity that results is changes of the path length that are frequency dependent.

This effect limits the maximum bandwidth which may be transmitted through the ionosphere

Atmosphere: band-pass filter

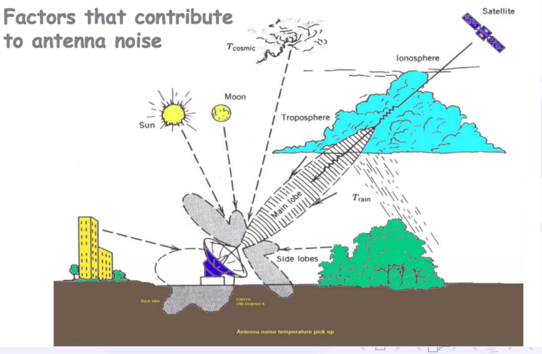


- f_1 depends on the refractive index of the ionosphere;
- f_2 depends on gaseous absorption;
- the maximum signal bandwidth depends on dispersion.

Within the admissible frequency range, atmospheric effects, e.g.; rain, must be accounted for.

Antenna noise temperature

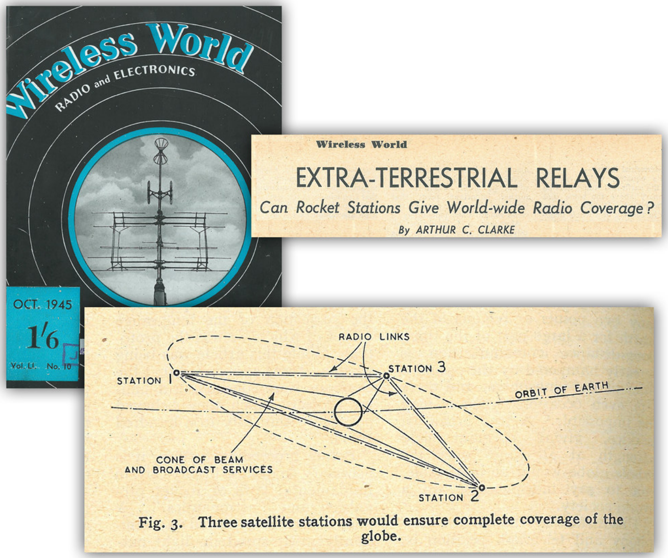
A common approach to analyze link budget in satellite communication is including all the effects previously mentioned in an effective noise temperature for sky and ground that is further combined with the receiver noise temperature to obtain the overall system temperature.



Outline

Arthur C. Clarke: from fiction. . .

. . . GEO Satellites as TLC relay stations

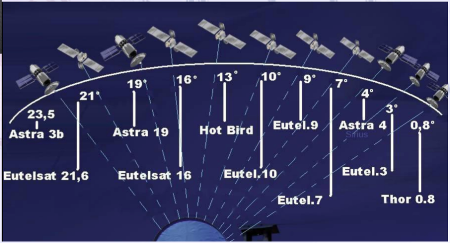


Fixed uplink stations

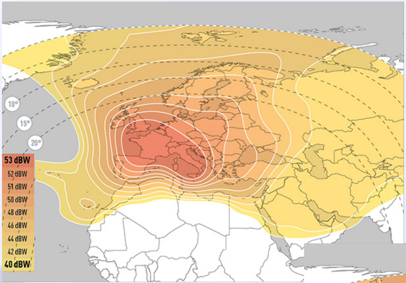
Mobile uplink stations

Mobile uplink station

Satellite relay stations



Uplink/Downlink coverage maps HotBird13E

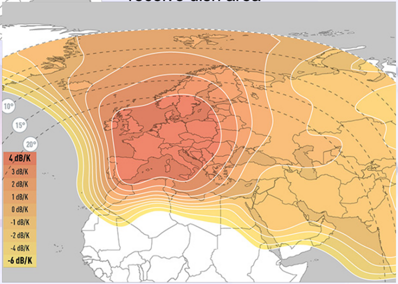


The satellite downlink beam coverage maps show contour lines where each line refers to a particular power level from the satellite. The lines are marked with EIRP values.

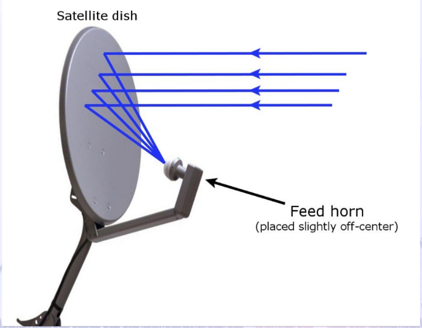
A reduction in power level means you need a larger receive dish area

Uplink Gain to Noise Temperature contours (dB/K) refer to the sensitivity of the satellite receive system to signals sent up from the ground.
Larger sensitivity allows smaller TX antenna dish size.

Local coverage vs hemi coverage

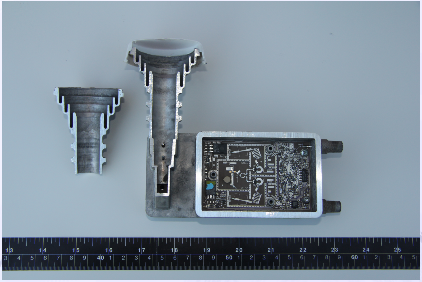


Parabolic dish antenna and feedhorn



The parabolic shape of a dish reflects the signal to the dish's focal point where a feedhorn collect it. The feedhorn is essentially the front-end of a metal waveguide that sends the received signal to a low-noise block downconverter (LNB).

LNB



It converts the incoming signal to a lower frequency (between 950 and 2150 MHz that can be easily transmitted through a coaxial cable) and amplifies it.

LNB

In smaller, newer satellite dishes the LNB is part of the feedhorn itself. It allows managing signal polarization switching back and forth between two different antenna probes (horizontal and vertical) within the LNBF itself.

Outline

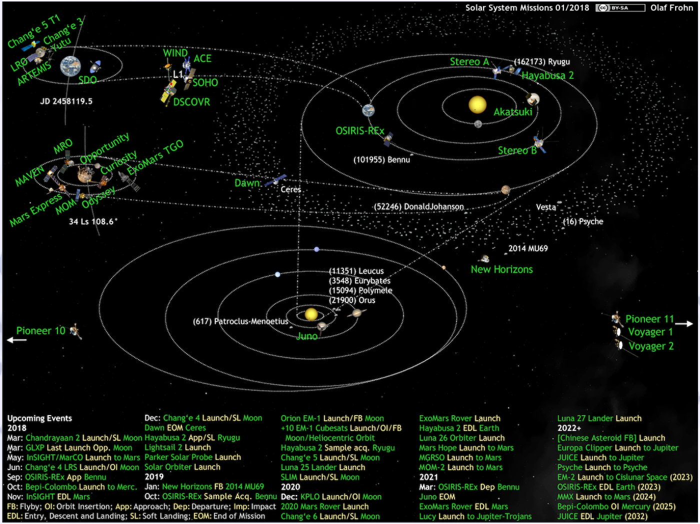
Deep space

Deep space exploration

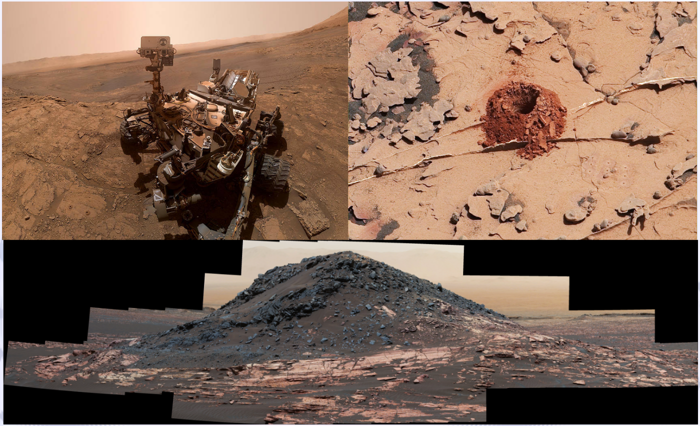
It is the branch of astronomy, astronautics and space technology that is involved with exploring the distant regions of outer space.

According to ITU deep space starts at a distance of 2 million km from the Earth's surface.

Active probes that escaped the Earth orbit

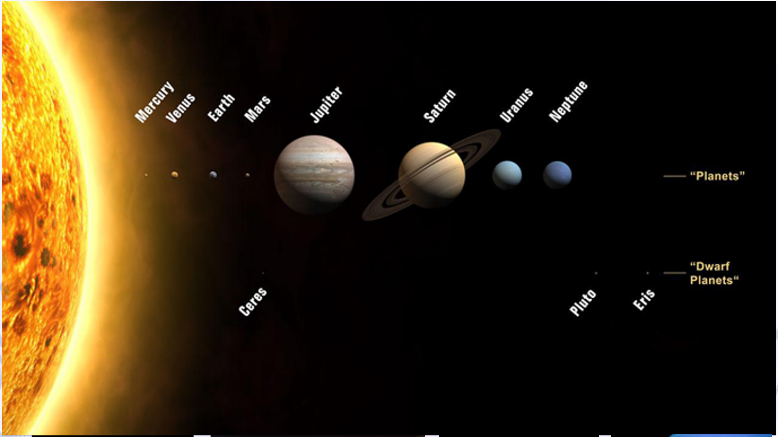


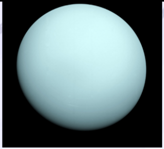
Nice pictures from the Mars curiosity mission

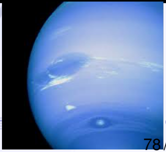


Mars-Earth distance varies between 55 – 400 millions km

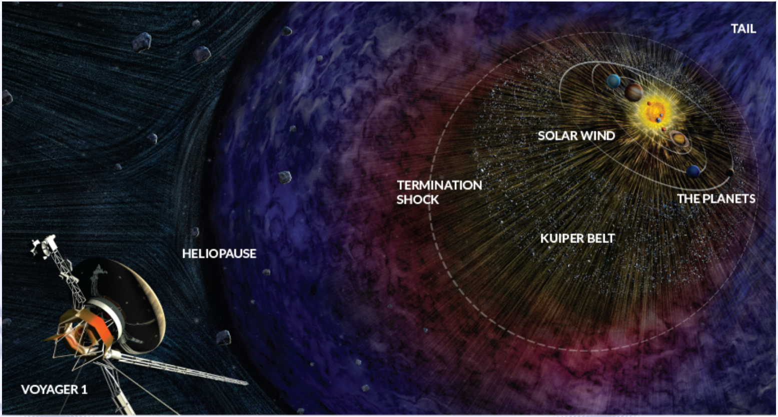
Nice pictures from the Voyager 1/2 spacecraft. . .







...which is now in the interstellar space



Voyager 1 is now >20 billion km from Earth

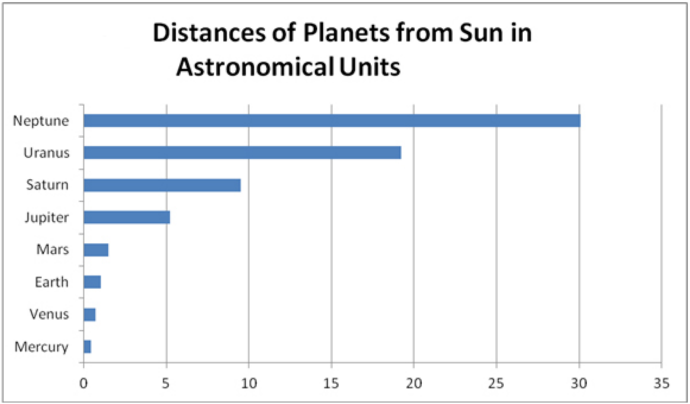
Mission status

	Voyager 1	Voyager 2
Launch Date	Mon, 05 Sept 1977 12:56:00 UTC	Sat, 20 Aug 1977 14:29:00 UTC
Mission Elapsed Time	42 : 06 : 21 : 18 : 58 : 03 YRS MOS DAYS HRS MINS SECS	42 : 07 : 06 : 17 : 25 : 03 YRS MOS DAYS HRS MINS SECS
Distance from Earth	13,804,132,822 mi	11,492,169,733 mi
	148.50214847 AU	123.63050385 AU
Distance from Sun	13,829,903,827 mi	11,473,783,582 mi
	148.77938788 AU	123.43270924 AU
Velocity with respect to the Sun (estimated)	38,026.77 mph	34,390.98 mph
One-Way Light Time	20:35:03 (hh:mm:ss)	17:08:12 (hh:mm:ss)
Cosmic Ray Data		

Nice app available at:

`https://eyes.jpl.nasa.gov/eyes-on-voyager.html`

Solar system - distance of the planets - AU



An astronomical unit (AU) represents the mean Earth-to-sun distance. It is approximately 8 light-minutes, i.e.; about 150000 km.

Voyager 1 - Link budget

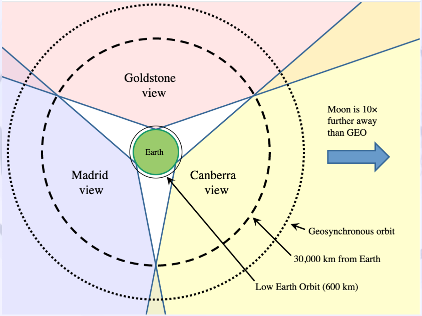
$$P_R = P_T + G_T - L_F + G_R \qquad [dB] \qquad (11)$$

- In the downlink channel, a high gain (48dBi) X-band (8.4GHz) antenna is used.
- The transmitted power is equal to 13.4dBW
- The main source of attenuation if the free space path loss which, at the distance of 22.3 billion km, gives about 337dB!
- The received power is about 20 billion times weaker than that of a digital wristwatch.

To receive such an extremely weak signal, a huge receiving dish antenna is needed!

Deep space network

It is a worldwide network of U.S. spacecraft communication facilities, located in the United States, Spain, and Australia, that supports NASA's interplanetary spacecraft missions.



- Three sites guarantee full-time visibility.
- The sites are equipped with ultra-sensitive receiving systems and large parabolic-dish (34m, 26m, 70m) antennas.

Deep space network - 70m dish antenna

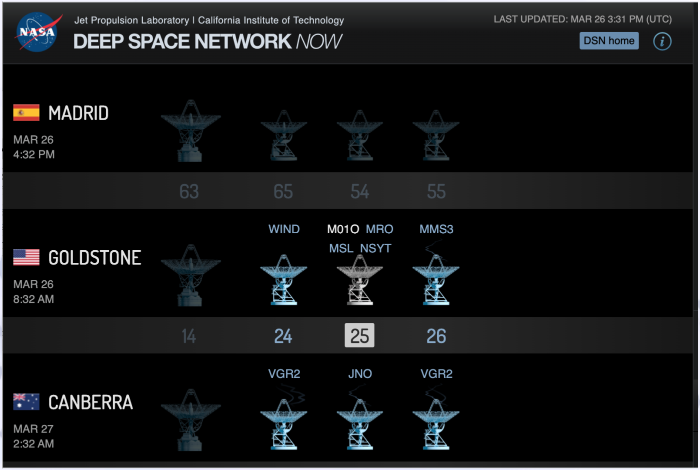
- The gain of the dis antenna can be approximated as follows:

$$G \approx \left(\frac{\pi d}{\lambda}\right)^2 \eta_a$$

- Hence, the gain is about 73dB

$$P_R = 13.4 + 48 - 337 + 73 = -202.6 \quad dBW \qquad (12)$$

Deep space network



https://eyes.nasa.gov/dsn/dsn.html