SMALL SATELLITE LINK BUDGET CALCULATION

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Critical points in a Satellite Link

Critical points in a Satellite Link

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- Available power at the satellite
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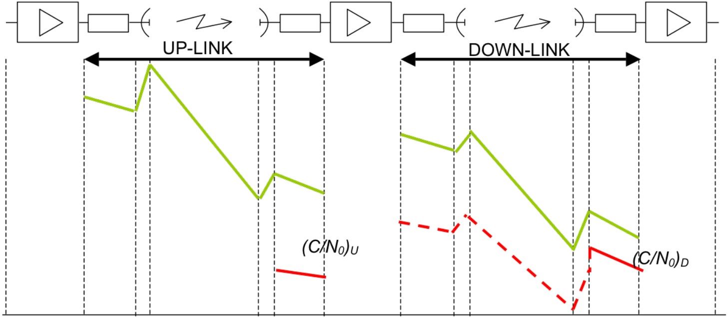
Radio link chain



RECOMMENDATION ITU-R P.525-2

RECOMMENDATION ITU-R P.525-2

- Friis formula was first published in 1946: H. T. Friis, 'A note on a simple transmission formula,' Proc. IRE 34, 254–256 (1946)
- $p_r = p_t \cdot (1 - |\Gamma_t|^2) \cdot g_t \cdot \left(\frac{\lambda}{4\pi \cdot d}\right)^2 \cdot \frac{1}{a_m} \cdot g_r \cdot (1 - |\Gamma_r|^2)$, where Γ_t and Γ_r are the reflection coefficients of the antennas and g_t and g_r the gain of the antennas
- $p_r = p_t \cdot (1 - |\Gamma_t|^2) \cdot g_t \cdot \frac{1}{4\pi \cdot d^2} \cdot \frac{1}{a_m} \cdot A_{eff} \cdot (1 - |\Gamma_r|^2)$, where $A_{eff} = \frac{\lambda^2}{4\pi} g_r$ is the effective area of recepction

Free-space basic transmission loss

Free-space basic transmission loss

- If the distance d between the antennas is much greater than the wavelength λ, the free-space attenuation (free-space basic transmission loss) in decibels will be: $L_{bf} = 20 \cdot \log_{10}\left(\frac{4\pi \cdot d}{\lambda}\right)$
- With a low-orbit satellite with elliptical orbit, the distance must be calculated using the worst case, that means when the satellite is with the lowest elevation angle and in the direction of the major axis of the ellipse

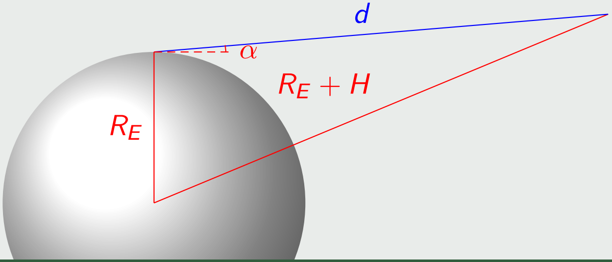
Maximum distance

Maximum distance

- The maximum distance with a satellite with maximum height H and minimum elevation angle α is:

$$d_{max} = -R_E \sin\alpha + \sqrt{(R_E \sin\alpha)^2 + H^2 + 2 \cdot R_E \cdot H}$$

Satellite distance



HUMSAT: Distance and time

Orbit altitude (Km)	Elevation angle	Maximum link distance (Km)	Link time (s)
400	40	598	60
	50	512	43
	60	457	30
600	40	882	90
	50	761	65
	60	683	45
800	40	1159	119
	50	1006	87
	60	907	61

RECOMMENDATION ITU-R P.341-5

RECOMMENDATION ITU-R P.341-5

- The basic transmission loss of a radio link (L_b) is the addition between the free-space basic transmission loss (L_{bf}) and the loss relative to free space (A_m): $L_b = L_{bf} + A_m$
- Main types of losses for satellite communications:
  - absorption loss (ionospheric, atmospheric gases or precipitation)
  - effective reflection or scattering loss as in the ionospheric case including the results of any focusing or defocusing due to curvature of a reflecting layer
  - polarization coupling loss from any polarization mismatch between the antennas for the particular ray path considered
  - effect of wave interference between the direct and reflected rays from the ground, other obstacles or atmospheric layers

Antenna Gain and Beamwidth

Antenna Gain and Beamwidth

- The Beamwidth of a pattern is defined as the angular separation between two identical points on opposite side of the pattern maximum
- One of the most widely used beamwidths is the Half-Power Beamwidth (HPBW) that can vary with the azimuth angle
- An approximate relation between the antenna gain and its HPBW is $g_{max} = \frac{4\pi}{HPBW_E \cdot HPBW_H}$

Polarization

Polarization

- The polarization in the link can be Lineal, Horizontal or Vertical, or Circular, Left Hand (LHCP) or Right Hand (RHCP)
- Both antennas (satellite and earth station) should have the same polarization.
- Theoretically, using two orthogonal polarizations, radio-link capacity can be the double, but a crosspolarization interference can appear in the reception

Recommendation ITU-R P.618-12

Propagation data and prediction methods required for the design of Earth-space telecommunication systems

- In the design of Earth-space links for communication systems, several effects must be considered:
    - absorption in atmospheric gases; absorption, scattering and depolarization by hydrometeors and emission noise from absorbing media and they are especially important at frequencies above about 10 GHz
    - loss of signal due to beam-divergence of the earth-station antenna, due to the normal refraction in the atmosphere
    - a decrease in effective antenna gain, due to phase decorrelation across the antenna aperture, caused by irregularities in the refractive-index structure

Recommendation ITU-R P.618-12 (II)

Propagation data and prediction methods required for the design of Earth-space telecommunication systems

- Continue:
  - relatively slow fading due to beam-bending caused by large-scale changes in refractive index; more rapid fading (scintillation) and variations in angle of arrival, due to small-scale variations in refractive index
  - possible limitations in bandwidth due to multiple scattering or multipath effects, especially in high-capacity digital systems
  - attenuation by the local environment of the ground terminal
  - short-term variations of the ratio of attenuations at the up- and down-link frequencies, which may affect the accuracy of adaptive fade countermeasures
  - for non-geostationary satellite (non-GSO) systems, the effect of varying elevation angle to the satellite

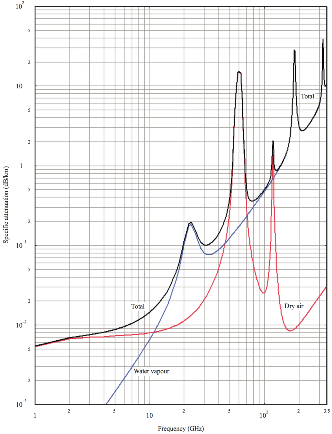
Recommendation ITU-R P.618-12 (III)

Ionospheric effects (see Recommendation ITU-R P.531)

- Effects of the non-ionized atmosphere become critical above about 1 GHz and for low elevation angles
- These effects are:
    - Faraday rotation: a linearly polarized wave propagating through the ionosphere undergoes a progressive rotation of the plane of polarization;
    - dispersion, which results in a differential time delay across the bandwidth of the transmitted signal;
    - excess time delay;
    - ionospheric scintillation: inhomogeneities of electron density in the ionosphere cause refractive focusing or defocusing of radio waves and lead to amplitude and phase fluctuations termed scintillations

Attenuation by atmospheric gases. Recommendation ITU-R P.676-10

Specific attenuation due to atmospheric gases



Pressure: 1 013 hPa
Temperature: 15° C
Water vapour density: 7.5 g/m³

Attenuation by rain

Attenuation by rain

- The attenuation by rain is calculated using the Specific attenuation (dB/Km) and the Effective rain path (Km)
- Specific attenuation γ_R is computed with the rainfall rate R_p (mm/h) exceeded for % of an average year, typically $p = 0.01$ that provides a QoS of 99.99%.
- The effective path length L_e is computed including the effect of the height of the terrain, elevation angle, longitude and latitude.

Rainfall Rate

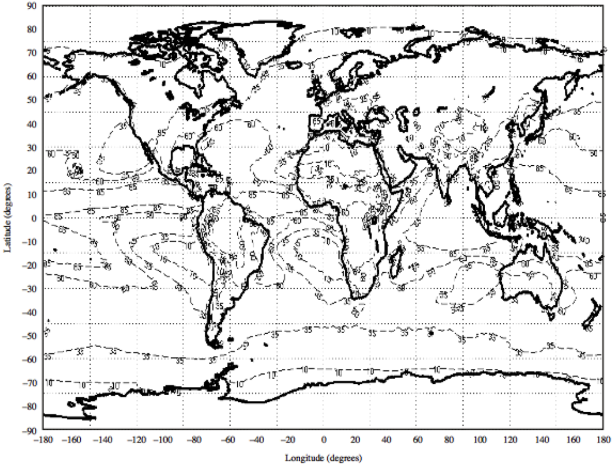


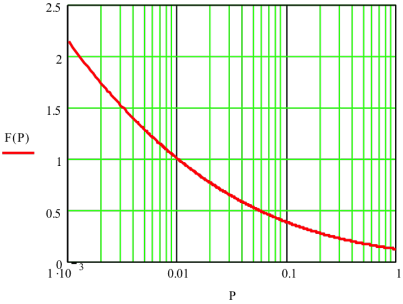
FIGURE 1

Rain rate (mm/h) exceeded for 0.01 % of the average year

Attenuation by rain $p \neq 0.01$

Attenuation by rain $p \neq 0.01$

- The rain attenuation for different availability of 99.99% ($p = 0.01\%$) can be computed using the following graph:



Rain, fog and clouds

Cross polarization due to the rain

- The rain drop shape is elongated
- This implies that the rain can be considered as an isotropic media for the electromagnetic wave propagation.
- Crossing the wave through a rain area, a cross polarization effect appears due to this effect.

Attenuation due to clouds and fog. Recommendation ITU-R P.840-5

- It is quite equivalent to the rain attenuation method
- The attenuation values are smaller

Estimated ionospheric effects for elevation angles of about 30^o

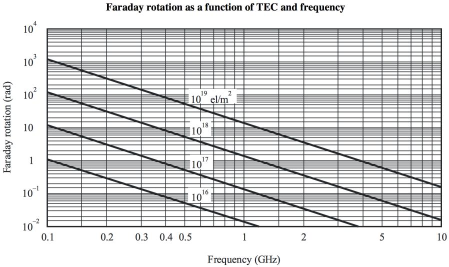
Estimated ionospheric effects for elevation angles of about 30^o

- The effects at 500 MHz are:
  - Faraday rotation 1.2 rotations
  - Propagation delay $1\mu s$
  - Refraction $< 2.4'$
  - Variation in the direction of arrival (r.m.s.) 48"
  - Absorption (auroral and/or polar cap) 0.2dB
  - Absorption (mid-latitude) $< 0.04dB$
  - Dispersion 0.0032 ps/Hz
  - Scintillation up to 27.5 dB

Faraday rotation

Faraday rotation

- When propagating through the ionosphere, a linearly polarized wave will suffer a gradual rotation of its plane of polarization due to the presence of the geomagnetic field and the anisotropy of the plasma medium



Scintillation

Scintillation

- Scintillations are created by fluctuations of the refractive index, which are caused by inhomogeneities in the medium
- It is important for signals below 3 GHz but the effects may be observed occasionally up to 10 GHz
- Geographically, there are two intense zones of scintillation, one at high latitudes and the other centered within 20^o of the magnetic equator. In the middle latitudes scintillation occurs exceptionally, such as during geomagnetic storms. In the equatorial sector, there is a pronounced night-time maximum of activity

HUMSAT-D: Atmospheric losses at 437 MHz

Elevation	Minimum L_{atm} (dB)	Maximum L_{atm} (dB)	Minimum L_{sci} (dB)	Maximum L_{sci} (dB)
5	0.02	0.22	0.02	0.37
10	0.02	0.11	0.02	0.16
15	0.02	0.08	0.02	0.1

Recommendation ITU-R P.372-12

Radio Noise

- The noise can be produced by:
    - Radiation from lightning discharges
    - Aggregated unintended radiation from electrical machinery, electrical and electronic equipments, power transmission lines, or from internal combustion engine ignition (man-made noise)
    - Emissions from atmospheric gases and hydrometeors
    - The ground or other obstructions within the antenna beam
    - Radiation from celestial radio sources

Noise model

Noise model

- Additive Gaussian White Noise
- Noise power spectral density of n_0 constant
- Noise Power $n = n_0 \cdot b$ where b is the bandwidth
- Effective noise temperature (Kelvin) at a reference point of the circuit $t = \frac{n_0}{k}$ where $k = 1.379 \cdot 10^{-23} W \cdot Hz^{-1} \cdot K^{-1}$
- So, $n = k \cdot b \cdot t$

Internal effective noise temperature

Internal effective noise temperature

- Effective noise temperature t_{ef} of a two port circuit (for example, an amplifier) referred at the entrance: $n_{out} = (n_{in} + n_{ef}) \cdot g = k \cdot b \cdot (t_{in} + t_{ef}) \cdot g = k \cdot b \cdot t_{out} \Rightarrow t_{out} = (t_{in} + t_{ef}) \cdot g$
- Internal noise factor: $f_n = 1 + \frac{t_{ef}}{T_0}$ where the reference temperature $T_0 = 290K$
- External noise factor: $f_a = \frac{t_{in}}{T_0}$
- System noise factor: $f = \frac{t_{in}+t_{ef}}{T_0}$
- Noise Figure $F = 10 \cdot \log_{10} f$

Effective Noise Temperature of a transmission Line

Effective Noise Temperature of a transmission Line

- The effective noise temperature for a resistive attenuator (with attenuation a) at physical temperature t_{phy} temperature is $t_{ef} = t_{phy} \cdot (a - 1)$
- This model is applied for any attenuator including transmission lines for both transmission and reception chains

HUMSAT-D: Ground Station Receiver Chain

	Transm. Line 1	Transm. Line 2	Pre-amplifier	Transm. Line 3
Gain (dB)	-0.9	-0.11	20	-1.53
Gain	0.813	0.975	100	0.703
Noise Figure (dB)	0.9	0.11	0.9	1.53
Noise Temp. (K)	66.8	7.4	66.8	122.5
Total noise temp. at input	66.8	$66.8 + \frac{7.4}{0.813} = 75.9$	$75.9 + \frac{66.8}{0.793} = 160.14$	$160.14 + \frac{122.5}{79.3} = 161.68$

Antenna Noise

Antenna Noise

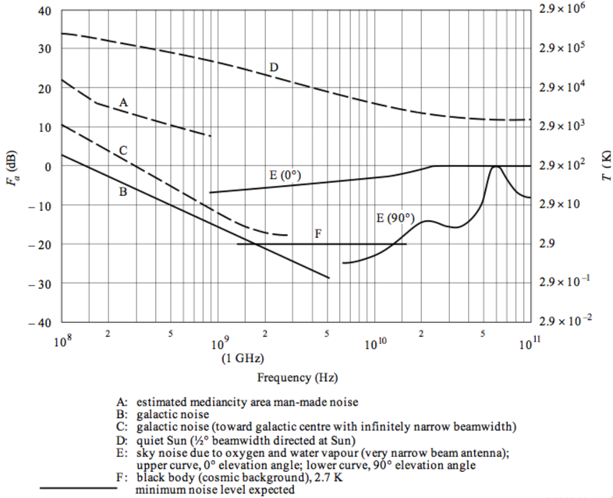
- The antenna noise is modelled by an equivalent temperature t_A
- The antenna noise picks up an average of the brightness temperature of the radiation bodies around the antenna, weighted by the antenna pattern radiation: $t_A = \frac{1}{4\pi} \int \int t_B \cdot g_r(\theta, \phi) \sin\theta d\theta d\phi$

Noise temperature of a satellite antenna

Noise temperature of a satellite antenna

- For the uplink, satellites with attitude control and a directive antenna that points to the Earth, the antenna temperature can be considered as $T_0 = 290K$, but this value is considered as default if we don't have further information
- For the downlink, the antenna noise sources are the temperature of clear sky t_{CS}, the temperature due to radiation sources t_{FR} (Sun, Moon), the temperature of the ground t_{GROUND} (by side lobes), the additional temperature when it is raining t_{RAIN} with a hydrometeor temperature t_m and attenuation a_{RAIN}: $t_A = \frac{t_{CS}+t_{FR}+t_m \cdot (a_{RAIN}-1)}{a_{RAIN}} + t_{GROUND}$

RECOMMENDATION ITU-R P.372-12



A: estimated mediancity area man-made noise
B: galactic noise
C: galactic noise (toward galactic centre with infinitely narrow beamwidth)
D: quiet Sun (½° beamwidth directed at Sun)
E: sky noise due to oxygen and water vapour (very narrow beam antenna); upper curve, 0° elevation angle; lower curve, 90° elevation angle
F: black body (cosmic background), 2.7 K
— minimum noise level expected

HUMSAT-D: Total Noise

	Antenna Noise	System Noise	Receiver Noise
Gain		55.75	
Gain (dB)		17.5	
Noise Temp. (K)	400	161.8	2400
Total noise temp. at input	400	$400 + 161.8$ $= 561.8$	$561.8 + \frac{2400}{55.75}$ $= 604.8$

Rate carrier / noise

Rate carrier / noise

- C/N: Relation between the power of the modulated carrier C and the noise power
- C/N_0: Relation between the power of the modulated carrier C and the noise power spectral density $N_0 = k \cdot t$. It can characterize the channel without the final information about the bandwidth
- $C/N_0 = \frac{\frac{EIRP}{L_b} g_r}{k \cdot t} = \frac{EIRP}{L_b} \left(\frac{g_r}{t}\right) \frac{1}{k}$

Doppler effect

Doppler effect

- The Doppler effect is the change in frequency of a wave for an observer moving relative to its source
- All non-geostationary satellite moves relative to the Earth-Station, so a Doppler effect appears.
- The change in frequency can be calculated as $\Delta f = \frac{\Delta v}{c} f_0$
- This shift increases with the frequency of the carrier f_0 and in LEO. At 800 Km and 435 MHz, the doppler shift can be $\pm 9.76 KHz$ at low elevation angles
- The receiver must compensate this shift estimating the position of the satellite or it must increase the bandwith and the noise

E_b/N_0

E_b/N_0

- For the purposes of link budget analysis, the most important aspect of a given modulation technique is the Signal-to-Noise Ratio (SNR) necessary for a receiver to achieve a specified level of reliability in terms of BER
- $E_b/N_0 = SNR \cdot \frac{b}{R_b}$ where R_b is the system data rate and E_b is the energy per bit of information
- In general, the modulation technique dictates the required system bandwidth

Receiver sensitivity

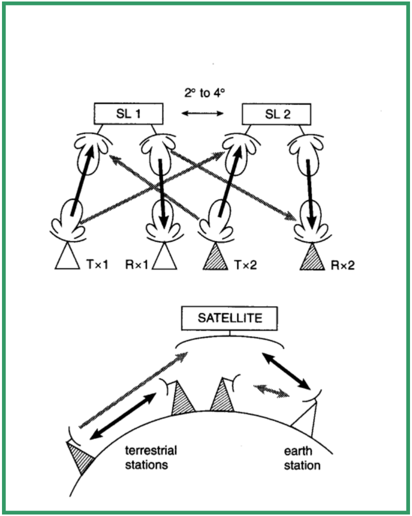
Receiver sensitivity

- The first step in performing the link budget is determining the required signal strength at the receiver input. This is referred to as receiver sensitivity
- As described previously, this is a function of the Modulation Technique and the desired BER
- As an example, PSK modulation requires $E_b/N_0 = 9.5dB$ to achive a $BER = 10^{-5}$. Then its sensitivity will be the internal noise plus 9.5 dB.

HUMSAT-D: Receiver noise

Sensitivity (dBm)	-118
Sensitivity (dBW)	-148
SNR (dB)	13
Bandwidth (kHz)	2.4
Noise Temperature (K)	$\frac{10^{-14.8}}{10^{1.3}\cdot 2400\cdot 1.379\cdot 10^{-23}} = 2400$

Interference



Summary for computation of the Link Budget

Summary for computation of the Link Budget

- Compute the received power at the entrance of the receiver. It must be higher than the sensitivity
- Compute the noise received by the antenna
- Define the reference point to compute the performance of the Link Budget. Typically at the entrance of the receiver or at the entrance of the LNA
- Use the SNR and/or E_b/N_0 methods to determine if we have achieved the required margins

Methods for computation of the Link Budget

Methods for computation of the Link Budget

- Method 1 : SNR Method (More realistic). Usually, the Link budget is computed to provide a SNR greater than minimum SNR at the entrance of the LNA of the receiver. For this method it is necessary to know the bandwidth used by the receiver
- Method 2 : E_b/N_0 Method (less realistic). It is assumed that the receiver uses the minimum possible bandwidth

HUMSAT-D: Link budget

Transmitter power	0.5 W
Transmitter power	27 dBm
TTC antenna gain	-6 dBi
Transmission Losses	0.1 dB
Tx Impedance mismatch	0.5 dB
EIRP	$27 - 6 - 0.1 - 0.5 = 20.4dBm$

Distance (H=800 Km, $\alpha = 15^o$, f=437 MHz)	2030 Km
Free-space basic transmission loss	151.4 dB
Atmospheric loss	0.18 dB
Polarization loss	3 dBi
Basic transmission loss	154.58 dB

HUMSAT-D: Link budget II

GS Antenna Gain	18.95 dBi
Unpointing loss	1 dB
Rx Impedance mismatch	0.51 dB
Received power	20.4-154.58+18.95-1-0.51 = -116.74 dBm
Received power at receiver	-116.74+17.5 = -99.24 dBm
Margin with sensitivity	-99.24-(-118) = 18.76 dB
Bandwidth	5 KHz
Noise	$604.8 \cdot 1.379 \cdot 10^{-23} \cdot 5000 = 4.2 \cdot 10^{-17} W$
Noise	-133.8 dBm
SNR	-116.74-(-133.8) = 17.06 dB
SNR Minimum	13 dB
Margin	17.06-13 = 4.06 dB

Low elevation angle

Low elevation angle effects

- Greatest distance with the satellite
- Maximum Doppler shift
- Maximum atmospheric losses
- Greater noise (man-made and Earth noise)
- Ground reflection

Difference between small and large satellites

Difference between small and large satellites

- The antenna gain at the satellite is smaller
- The transmitted power from the satellite is also smaller
- If the satellite doesn't have attitude control, the gain and the polarization can change over time. The worst case must be calculated
- It is useful to implement a dual receiver with two orthogonal polarizations

More information

More information

- AMSAT-IARU Link Budget
- For non comercial purposes

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