Satellite Links, Link-Budgets

Calculating satellite links (link-budgets) is hard to do manually. Satlinker is a practical approach to all satellite and ground station related calculations without overhead. To find the satellite, you first need to know the exact direction to it from your location, so a pointing angle calculation to a reference satellite is included. Then you want to know if the connection to the satellite is possible with your equipment. Maybe you want to make transmissions to other countries or even build your own station. Satlinker helps you with all these things. Especially for SNG, Flyaway, respectively Digital Video Broadcast (DVB, DVB-S2) in general, the established modulation methods are included. The program is written in LibreOffice Calc, but unfortunately doesn't support Microsoft Excel any more due to incompatibilities of programming languages. Give LibreOffice a chance, it's almost identical to Excel, freeware and also runs under Linux.

Satlinker is written for technicians, so you should have a basic understanding of that high frequency stuff... Please read the short tutorials, then ask, not vice versa. You can download the program for free, please respect the LGPL License. I am looking forward to a short message from you, describing who you are and why you need that stuff. **Please use only for non-military projects** -stay peaceful.

Satlinker vs Satmaster

Satlinker is a freeware, opensource link-budget calculator. You can verify the whole link-budget calculation and even modify formulas if you want. Satmaster is a commercial program from Arrowe that includes satellite and location databases. For both programs you need an understanding of the whole process. You need data of satellites and ground stations that are not easy to get. You cannot get realistic link-budgets without knowledge, so it's not enough to have a good program! Please take a look at this manual in the overviews of Earth Stations and Transmission Path to get an idea about the difficulties. If you have any technical problems or look for SNG-training, please contact me.

Link-Budget Calculator

This tutorial does not describe the principles and basic formulas of a link-budget calculation, you can learn these things in various other places e.g. here. Here we discuss how to get the right data and how to use this link-budget calculator.
Attention: If you don't use the english user interface of LibreOffice, set the option:
Tools - Options - Load/Save - HTML_Compatibility - Import, Use_English(USA)_locale_for_numbers.
At program start you will be asked to enable macros and update links. You must enable macros, but there is an option to disable this question. If you are connected to the internet, press yes to update links and after a short time the newest satellite data are downloaded. The program seems to freeze while download is in progress, just wait some seconds. There are some station data and approved sample link-budgets included. You can take them as a guideline or delete them if you don't need it.

Program handling

If you want to insert columns, copy an existing column, so all formulas in the cells will also be duplicated, then modify the copied data. I know this is not what you expect from a "real" program, but so you can get most flexibility and have lots of calculations on one sheet. So if you want to insert a new station or make a new link-budget, copy the first example column, insert it into an empty column and modify all but red cells. The red cells contain formulas and will be calculated automatically.

Some data in a table is related to data in another table e.g. if you type the name of a location in the link-budget table, the program gets the coordinates for this location from the Loc table. So location-, station- and IRD-names are linked with data in their corresponding tables. In the first column there is a tooltip help in cells with a red dot in the upper right corner.

The Point tab is a database for satellite related data. Satellites are imported automatically from N2YO. The table shows the azimuth, elevation and other angles to each satellite from the location that you can specify in the gray cell in first row. The difference angle to a reference satellite is also displayed, that is a pointing help for uplinkers. The names of the location and the reference satellite must exist in the Loc and Point tables.

The Loc tab contains location data, available at Heavens Above or at Earth Info. Write the data of your location(s) or the next town near you.

The IRD tab describes the quality of the IRD with a minimum needed Eb/N0 in dependence of FEC. ETS300421 specifies a minimum Eb/N0 for a BER of 2×10^{-4} after inner decoding (post Viterbi). That is Quasi Error Free (QEF ~ 10^{-11}) after outer decoding (post Reed Solomon). However modern IRDs are better, I included the data of modern decoders, that slightly depends on the symbol rate. The quality of the inner decoder depends on the number of errors that it can correct and not only detect.

The Earth station related data must be filled only once for your specific antenna.

The Link-budget tab contains a link in each column. Satellite related data must be filled in the green cells, earth stations related data in the blue cells. Results will be calculated by software in the red cells.

The program calculates the needed usable HPA power for the uplink station from the EIRP that you entered. You need to know the maximum radiated "usable" HPA power (flange power) e.g. from a power meter measured behind the HPA output, it's not always equal to the HPA power specification! The HPA must be operated with a back off and cannot be driven into saturation. That is also the reason why TWTAs cannot be compared directly with SSPAs, only usable power or EIRP are unambiguous (contact me for further details to actual HPAs). If the TWTA is operated in the topmost 3dB of it's power specification (nominal power) it might produce a lot of distortion. So you should not use this range, you might disturb your neighbors on the transponder. Some TWTAs deliver more power than specified, because they loose power again when getting older.

For all who didn't recognize: the transistor has been invented. In the lower power range (up to about 150W) a SSPA has a better efficiency and handling. Especially big dishes can profit from a SSPA because there is no need to keep a tube warm in case of a power breakdown. New gallium nitride (GaN) transistors deliver up to 250W in the KU-Band and are not bigger than a shoe box.

To get the minimum needed power for the link, increase the EIRP of the uplink station as long as the "Link margin to Eb/N0min" becomes zero. If you increase EIRP as long as IBO reaches nominal IBO, you can see if your earth station has a satisfying power margin. If the satellites' transponder is full and gets saturated, adjust IBO-OBO like explained below and correct EIRP once again.

Satellite related data

Your greatest problem will be to get the satellites' data from the sat operators. Please fire questions at them to write the correct values on their homepages or on the channel bookings (often they don't know it off-hand). To show you how an accurate datasheet should look like, see the Hellas satellite. You need these things:

- G/T (Gain/Temperature) of transponder in satellite beam center and location disadvantage from G/T-footprint (satellite receive coverage).
- EIRP (Equivalent Isotropically Radiated Power) of transponder in satellite beam center and location disadvantage from EIRP-footprint (satellite transmit coverage).
- SFD (Saturation Flux Density) of transponder = Saturation IPFD (Input Power Flux Density).
- Transponder Operating Input Back Off ("nominal" IBO).
- IBO/OBO relation of the transponders' HPA (Input Back Off vs. Output Back Off).

The SFD needs some explanation. Often there is an SFD range in the datasheets, e.g. from -(92 + x) to -(77 + x), with x is the G/T location loss at the reception location. Each transponders' amplification can be remotely adjusted from the ground control room. Dependant on the actual amplification (also called gainsteps), you need another IPFD at the satellite dish to drive the transponders' HPA into saturation. The actual value must be obtained from the sat operator. For a worst case calculation take the most positive value, in our example -

(77 + x). Cause of the location dependancy of SFD, write the value for beam center (-77dB), the program does the rest for you.

The nominal input back off (IBO) is the minimal headroom to HPA saturation. If the transponders' HPA is driven up to saturation, it produces maximum output power but also distortion and a phase shift, especially TWTAs. To avoid these effects, the operator stops the feeds some dBs below. Each transponder in a satellite may have another IBO and therefor OBO. You will not find the nominal IBO in the datasheet, but it's not critical because the program only needs it to warn you if your EIRP is to high. IBO and OBO are both positive values in here because they are considered as headrooms, this can be different in literature.

The very important IBO vs. OBO relation depends on the HPA type in the transponder, that can be a TWTA (Traveling Wave Tube Amplifier), a linearized TWTA or a transistorized SSPA (Solid State Power Amplifier). It is slightly different for multicarrier and singlecarrier operation. Try to get the transponders' IBO vs. OBO curve or table from the sat operator and adjust "IBO-OBO" in the link-budget table according to the calculated IBO. As long as the amplifier is operated in the linear region, the curve is almost constant, so IBO minus OBO is constant too. Most amplifiers differ, so we have no generic formula for all. A typical approximation for a TWTA with digital multicarrier operation looks like that:
for IBO > 13dB: OBO = IBO - 7
for IBO ≤ 13dB: $OBO = 1.7 + 0.0313 \times IBO^2$

If the nominal IBO is > 13dB in this case, then the HPA is operated in the linear region and we have a constant IBO - OBO = 7dB. If IBO is < 13dB, you have to correct IBO - OBO and calculate again until you approach the result:
e.g. IBO = 6dB, OBO = 1.7 + 0.0313 × 36 = 2.83dB, IBO - OBO = 3.17dB
For further information look here in the TWTA tutorial.

Earth Stations

Station data are available from mancufacturers, if not ask them. You should get a databook and a measurement protocol for a professional station. Aperture and pointing accuracies are important parameters of a station. A big dish is of no use if it's not properly fixed or moved with inaccurate motors. Do not trust all consumer stuff data, like LNBs from the supermarket with a noise figure of 0.2dB, that's often not true.

Earth station related data

A	m^2	Antenna physical aperture area
c	m/s	speed of light = 2.997925×10^8
d	m	Parabolic antenna diameter
f	Hz	frequency
$F_{[dB]}$	dB	Noise figure
g_x	dBi	Antenna gain (relative to gain of an isotropic radiator that is linearly polarized)
λ	m	wavelength = c / f
η_x	1	Efficiency, a value between 0 and 1, or in %
P_r	W	Reflected power due to mismatched load
P_d	W	Delivered power that reaches the load
P_f	W	Forward power from the generator, also named incident power
T_{sys}	K	System noise temperature, see propagation theory site
$T_{sys,nom}$	K	Nominal system noise temperature used by component manufacturers

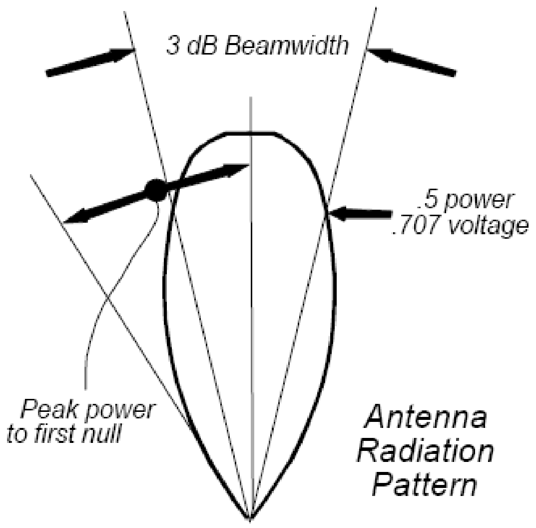
Parabolic dish types of construction

Antenna gain depends on dish size, dish profile accuracy, feed illumination and blockage from feed assembly. Whether the dish is circular or elliptical does not matter too much, assuming the feed is designed to match the dish shape by appropriately distributing the power across the dish surface. Typically the power density in the middle of the dish will be about 14dB higher than at the edges. 11dB edge taper gives a better gain, 16dB reduces the sidelobes.

In the uplink direction, the power spectral density you transmit into adjacent satellites must be limited by reducing sidelobe emissions. This may be achieved by reducing the power or under-illuminating the dish. Sidelobes are improved if there is little scattering from obstructions like the feed assembly or the dish edges. Also, having extended corners across a particular direction will help, so an elliptical or diamond shaped dish will have better sidelobe discrimination along its widest axis. If this axis is orientated along the orbit, interference to and from the adjacent satellites will be minimised (typically -28dB).

Poor cross-polarisation isolation causes interference to and from other services. It's very much a function of feed design and position. An offset feed has a bad cross-pol isolation and that is tried to compensate with a rather long and mechanically awkward focal length (f/d=0.8), or using a gregorian sub-reflector, or a special, expensive, mode-matched feed. Also adjusting the polarisation angle very carefully is essential. A cross-pol interference of -29dB is typical, perhaps -20dB in the worst case for the cheapest of receive only dishes.

Antenna half power beamwidth HPBW (3-dB beamwidth)



In a plane containing the direction of the maximum of a beam, the angle between the two directions in which the radiation intensity is one half the maximum value of the beam. HPBW depends on how the feed horn illuminates the dish. The cosine aperture illumination distribution is close to the average if the illumination method adopted is not known.

$\varphi_{3dB[deg]} = x / (f_{[GHz]} \times d_{[m]})$

aperture illumination distribution:	x:
uniform	17.508
cosine	21.825
cosine^2	25.243
pedestal	19.936

Pointing attenuation

In practice the pointing accuracy is normally kept within one third of the half power beamwidth. The bigger the parabolic dish, the smaller is it's beamwidth and the better it has to be pointed. But big dishes are more difficult to adjust and have a higher wind load. Dishes with diameters of about 5m and more are supplied with automatic tracking motors to correct pointing errors with the help of a tracking beacon.

φ_1 pointing accuracy dish to the satellite (≈ 10-30% of the half power beamwidth).

φ_2 pointing stability due to wind and ageing. (≈ 0.2-0.5 degrees)

φ_3 station keeping accuracy of the satellite (≈ ±0.16 degrees)

Pointing attenuation in dB: $a_{point} \approx 12 \times (\varphi_1^2 + \varphi_2^2 + \varphi_3^2) / (\varphi_{3dB})^2$

Efficiency of an aperture-type antenna

Aperture A: A surface near or on an antenna, on which it is convenient to make assumptions regarding the field values for the purpose of computing fields at external points. The aperture is often taken as that portion of a plane surface near the antenna, perpendicular to the direction of maximum radiation, through which the major part of the radiation passes.

Following efficiencies are defined very different in literature, but these definitions are the most logical ones:

Antenna efficiency η_a: is concerned with the effectiveness of an antenna in directing or collecting radiated power. It's the antenna system overall efficiency. It might be reduced to optimize other characteristics like low sidelobe level.

$$\eta_a = \frac{\text{effective area } A_e}{\text{physical aperture area } A} \text{ with } A_e = \frac{\text{terminal power } [W]}{\text{overall power density } [W/m^2]}$$

The effective area of a receiving antenna is the ratio of the delivered power at the antenna terminal to the power density over the whole aperture area. The antenna efficiency for a specified planar aperture is the effective area to the physical aperture area.

Aperture efficiency (illumination factor) $\eta_{ap} = \eta_{il} \times \eta_{sp} \times \eta_{bl} \times \eta_{re}$
Includes all efficiencies that affect aperture and radiation pattern, co and cross-pol components are included:

Illumination efficiency η_{il}: describes the variation in the electric field produced by a feed across an antenna surface. A uniformly illuminated dish with equal radiation intensity and without energy spilled past the edges is not achievable in practice, but useful as a reference. A non-uniformly illuminated dish produces amplitude (taper) and phase errors which means loss of directivity.

$$\eta_{il} = \frac{\text{directivity}}{\text{directivity of a uniformly illuminated antenna of the same aperture size}}$$

Surface tolerance efficiency: is included in taper and phase efficiency. In cassegrain antennas the shape of the subreflector is distorted to achieve uniform illumination across the main reflector. This results in a phase error that causes energy being radiated in undesired directions. That means an increase of the sidelobe level.

Spillover efficiency η_{sp}: represents the energy spilled over the edge of the main reflector (and subreflector of a cassegrain dish).

Blocking efficiency η_{bl}: The feed or the subreflector and support structure like fixing material shades off the main reflector which results in a smaller aperture.

Reflector transparency η_{re}: Energy may be radiated through the reflector, e.g. in mesh antennas.

Radiation efficiency η_{rad}: includes internal antenna losses like imperfect conductors, dielectrics and feed system dissipative energy which represents losses of waveguide components like feed horns, polarizers, orthomodal transducers...

$$\eta_{ad} = \frac{\text{total power radiated by antenna}}{\text{net power which antenna accepts from transmitter}}$$

Polarisation efficiency η_{pol}: The ratio of the power received by an antenna from a given plane wave of arbitrary polarisation to the power that would be received by the same antenna from a plane wave of the same power flux density and direction of propagation, whose state of polarisation has been adjusted for a maximum received power.

$$\text{Complex reflection coefficient } \Gamma = \frac{\text{reflected wave } v_r}{\text{forward wave } v_f} = \frac{Z_{load} - Z_0}{Z_{load} + Z_0}$$

Mismatch efficiency η_{vswr}: derived from reflection at the feed port and lossy waveguides due to impedance mismatch before the antenna. It can only be avoided under test conditions at a single frequency, not over a wide frequency band. Mismatch is therefor not part of antenna efficiency.

Γ describes both the magnitude ($|\Gamma|$) and the phase shift of the reflection:
$|\Gamma| = -1$: maximum negative reflection on a short-circuited line

$|\Gamma| = 0$: no reflection on a perfectly matched line
$|\Gamma| = +1$: maximum positive reflection on an open line

Voltage standing wave ratio (VSWR): e.g. VSWR 1.3:1 denotes a maximum standing wave magnitude that is 1.3 times greater than the minimum standing wave value. VSWR should not exceed 1.3:1, that corresponds to a return loss of 18dB and a mismatch efficiency of 0.983 (mismatch loss 0.075dB).
$VSWR = (1 + |\Gamma|) / (1 - |\Gamma|)$ a value between 1 and infinity

$$\text{Return loss} = 10 \times \log\left(\frac{\text{forward power } P_f}{\text{reflected power } P_r}\right) = -20 \times \log(|\Gamma|) = -20 \times \log\left(\frac{VSWR-1}{VSWR+1}\right)$$

$$\text{Missmatch efficiency } \eta_{VSWR} = \frac{\text{delivered power } P_d}{\text{forward power } P_f} = 1 - \Gamma^2 = 1 - \left(\frac{VSWR-1}{VSWR+1}\right)^2$$

Missmatch loss = $-10 \times \log \eta_{vswr}$ (minus sign because a loss is positive)

Power Standing Wave Ratio $PSWR = VSWR^2$

Cable attenuation between LNB and IRD is neglected. As a rule of thumb, cable attenuation should be 30dB lower than the gain of LNB, otherwise there is significant reduction of G/T.

Antenna gains

Directive gain g_d: is independent of actual power output and the distance of measurement. An isotropic radiator has a uniform spherical pattern with a directive gain of 0dB by definition. Radiation intensity in a given direction is the power radiated from an antenna per unit solid angle.

$$g_d = 10 \times \log\left(\frac{4 \times \pi \times \text{radiation intensity in a given direction}}{\text{total power radiated by antenna}}\right)$$

Directive gain is proportional to the aperture area and to the square of frequency! It neglects any losses, compared to the following gains.
Directivity = directive gain in the direction of maximum radiation.

Parabolic antenna directivity: $g_d = 10 \times \log(4 \times Pi \times A / \lambda^2) = 10 \times \log(4 \times Pi \times A \times (f / c)^2)$

Power gain g_p: In a physical media the ratio of the power flux per unit area from an antenna to the power flux per unit area from an isotropic radiator with the same power input. When the direction is not stated, usually the power gain in direction of maximum.

$$g_p = 10 \times \log\left(\frac{4 \times \pi \times \text{radiation intensity in a given direction}}{\text{net power which antenna accepts from transmitter}}\right)$$

$g_p = g_d + 10 \times \log(\eta_a) = g_d + 10 \times \log(\eta_{ap}) + 10 \times \log(\eta_{rad}) + 10 \times \log(\eta_{pol})$

Realized gain g_r: Power gain reduced by the loss due to mismatch of antenna input impedance to a specified impedance.
$g_r = g_p + 10 \times \log(\eta_{vswr})$

Emitted Isotropic Radiated Power EIRP[dBW] = g_r[dB] + P[dBW]

Figure of merit G/T

Nominal G/T describes the system quality in receiving direction under "nominal" conditions with θ_0 and $T_{sys,nom}$. This value can be found in manufacturers' datasheets. The antenna efficiency of the receiving path $\eta_{a,rx}$ might be slightly different to the transmitting path efficiency due to other waveguide components, therefore we use index rx. For calculation of T see the Transmission Path site.

$(G/T)_{nom} = 10 \times \log(G_d \times \eta_{a,rx} / T_{sys,nom}) = g_{p,rx} - 10 \times \log(T_{sys,nom})$

The usable G/T is declined by environmental influences on T and pointing attenuation:

$(G/T)_{sys} = g_{p,rx} - 10 \times \log(T_{sys}) - a_{point}$

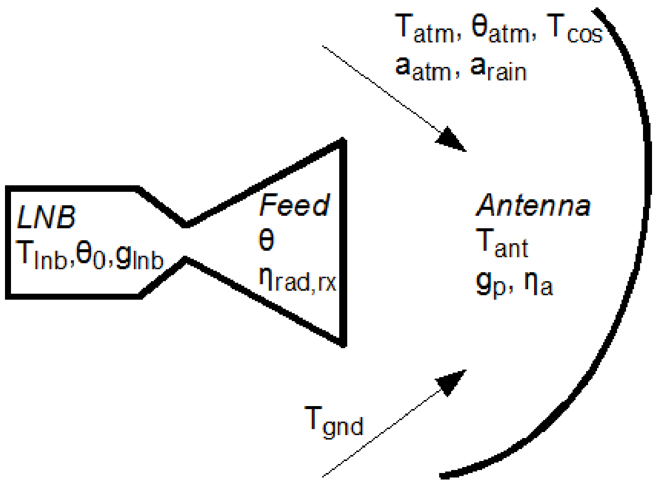
Literature

1. Digital Satellite Communications, Tri T. Ha, McGraw Hill
2. Antenna Introduction / Basics
3. Gain of Directional Antennas, John E. Hill, WJ Communications
4. Efficiency and sensitivity definitions for reflector antennas in radio-astronomy, Wim van Cappellen

Transmission Path

The calculation of noise is more complicated than commonly written. Environmental effects like rain cause not only an attenuation, but also increase the noise temperature, that has a great influence on the final result. Here we shall recapitulate some basics in noise theory and associate it with transmission.

Parabolic Antenna System



Physical temperatures are named θ and noise temperatures T. The values with index cs describe clear sky. The nominal values (index nom) will be calculated for a specific "nominal antenna noise temperature". These values are given by the component manufacturers and allow qualitative comparison between different stations. Unfortunately there is no standard for it. Satlinker calculates with vacuum, some manufacturers use clear sky condition to describe the system. Some calculate the data in relation to an elevation angle, others use only zenith elevation. These nominal values are not used for link-budget calculation because no operational margins are included such as antenna pointing or rain attenuation. See tooltip help for representative data.

a_{atm}	dB	Atmospheric absorption caused by humidity and oxygen in the atmosphere. a_{atm} is about 0.2dB at 15GHz, depends on frequency and elevation.
$a_{r,h2o}$	dB/km	Attenuation rate for water vapour, has nothing to do with fog or rain
$a_{r,o2}$	dB/km	Attenuation rate for oxygen
a_{rain}	dB	Rain attenuation due to absorption caused by rain drops
$\eta_{rad,rx}$	dB	Radiation efficiency, attenuation of waveguide components in receiving direction (feed horns, polarizers...)
B_n	Hz	Noise bandwidth
d	m	Parabolic antenna diameter
f	GHz	Frequency, here always in GHz!
F	1	Noise factor
$F_{[dB]}$	dB	Noise figure
k	W/(K×Hz)	Boltzmann constant 1.38×10^{-23} Joule/Kelvin
N	W	Noise power in Watt
φ_{el}	deg	Elevation angle
φ_{la}	deg	Latitude, north+, south-
ρ	g/m^3	The water vapour density at the surface of location of interest
R	mm/h	Point rain rate
s_0	km	Mean 0°C isotherm height, measured from mean sea level to sky

s_{al}	km	Altitude above mean sea level of location of interest
s_{el}	km	Slant path lenght along the elevation angle from location to s_0
θ	K	Physical temperature in Kelvin, at the location of interest
θ_0	K	Physical reference temperature 290K by definition in USA and Europe, 293K in Japan, used by component manufacturers
θ_{atm}	K	Atmospheric effective or mean radiating temperature
T	K	Effective noise temperature
T_{ant}	K	Antenna noise temperature
$T_{ant,nom}$	K	Antenna noise temperature used by component manufacturers. Might be 40K or another noise temperature, see description
T_{atm}	K	Atmospheric noise temperature
T_{cos}	K	Cosmic background noise temperature
T_{gnd}	K	Ground noise temperature, depends on dish elevation
T_{lnb}	K	LNB noise temperature

Gain, Attenuation, Transmissivity, Loss

These definitions are important for stated below noise temperature calculations.

Gain: $G = P_{out}/P_{in}$ for $P_{out} > P_{in}$ Gain in dB: $g = 10 \times \log G$

Efficiency: $\eta = P_{out}/P_{in}$ for $P_{out} < P_{in}$ Attenuation in dB: $a = 10 \times \log (1/\eta)$

Fractional transmissivity (Power dissipation) of serial connected resistors $R_1..R_i$ is defined as power dissipated in R_i to total power:

$\eta_i = P_i / P_{tot} = P_i / \Sigma_{[i=1..i]} (P_i) = R_i / \Sigma_{[i=1..i]} (R_i) = \mathbf{10^{-ai/10}}$

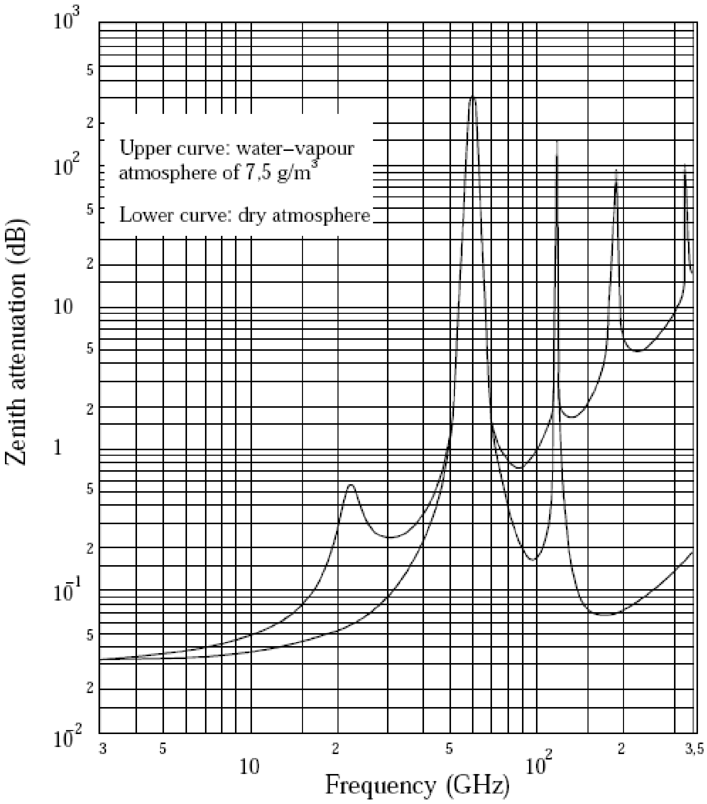
A loss has a unit e.g. [dBWatt], compared to gain or attenuation that have unit [1]:

Power Loss: $P_{loss} = P_{in} - P_{out} = P_{in} - P_{in} \times \eta = P_{in} \times (1 - \eta) = \mathbf{P_{in} \times (1 - 10^{-a/10})}$

Atmospheric attenuation a_{atm}

The diagram shows the zenith atmospheric attenuation $a_{atm,z}$ ($\varphi_{el} = 90°$).

For other elevations: $a_{atm} \approx a_{atm,z} / \sin(\varphi_{el})$, ($\varphi_{el} = 10°...90°$)



Simplified atmospheric attenuation model:
Main attenuations of the atmosphere are from water vapour and oxygen for f<57GHz:
Temperature correction factor: $x = 1 - 0.01 \times (\theta - 273.15 - 15)$
$a_{r,o2} = x \times [7.19 \times 10^{-3} + 6.09 / (f^2 + 0.227) + 4.3 / ((f - 57)^2 + 1.5)] \times f^2 \times 10^{-3}$
$a_{r,h2o} = x\times[0.0067 + 3/((f\text{-}22.3)^2+7.3) + 9/((f\text{-}183.3)^2+6) + 4.3/((f\text{-}323.8)^2+10)]\times f^2\times\rho\times10^{-4}$

The equivalent atmosphere height for oxygen (f < 57GHz) in km is: $s_{o2} = 6$km

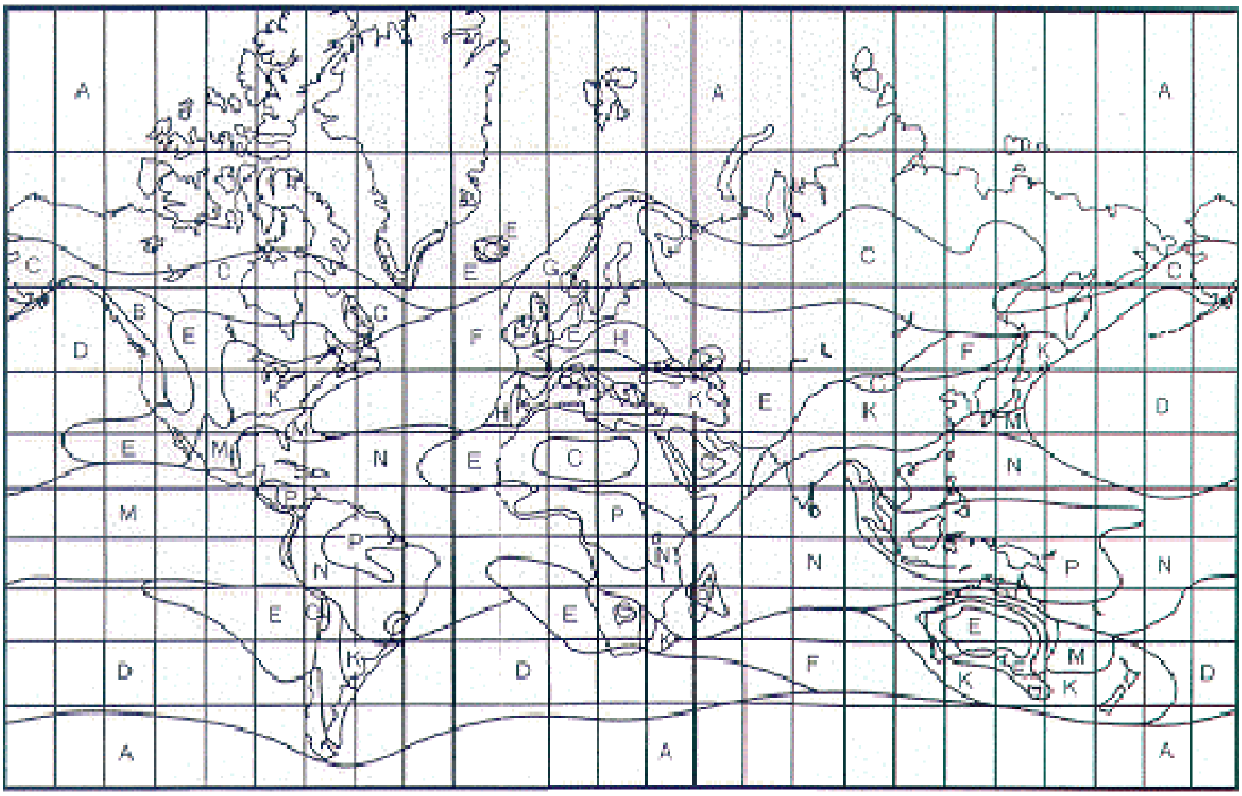
The equivalent atmosphere height for water vapour (f < 350GHz) in km is:
$s_{h2o} = 2.2 + 3 / ((f - 22.3)^2 + 3) + 1 / ((f - 183.3)^2 + 1) + 1 / ((f - 323.8)^2 + 1)$

The total slant path atmospheric attenuation for $\varphi_{el} > 10°$:
$a_{atm} = [a_{r,o2} \times s_{o2} \times e^{(-sal/so2)} + a_{r,h2o} \times s_{h2o}] / \sin(\varphi_{el})$

Rain attenuation a_{rain}

The rain attenuation depends on frequency, latitude, elevation and polarization. Here we use the "Simple Attenuation Model" (SAM) from Stutzman and Yen:
Latitude correction factor: $s_{la} = 4.8$ for $|\varphi_{la}| < 30°$ and $s_{la} = 7.8 - 0.1 \times |\varphi_{la}|$ for $|\varphi_{la}| > 30°$
s_0 with rain correction: $s_0 = s_{la}$ for R < 10mm/h and $s_0 = s_{la} + \log(R / 10)$ for R > 10mm/h
The slant path length: $s_{el} = (s_0 - s_{al}) / \sin(\varphi_{el}$
Rain attenuation for R < 10mm/h: $a_{rain} = x \times R^y \times s_{el}$
Rain attenuation for R > 10mm/h:
$a_{rain} = x \times R^y \times (1 - \exp(-s_{el} \times y \times z \times \ln(R / 10) \times \cos(\varphi_{el}))) / (y \times z \times \ln(R / 10) \times \cos(\varphi_{el}))$
$x = 4.21 \times 10^{-5} \times f^{2.49}$ (for 2.9GHz < f < 54GHz)
$x = 4.09 \times 10^{-2} \times f^{0.699}$ (for 54GHz < f < 180GHz)
$y = 1.41 \times f^{-0.0779}$ (for 8.54GHz < f < 25GHz)
$y = 2.63 \times f^{-0.272}$ (for 25GHz < f < 164GHz)
z = 1/14 this is an empirical determined value

For determining a rain rate R, pick a climate zone A to P for the transmitting or receiving location from the CCIR rain climate regions map, then look up the rain rate from table:



%/year	A	B	C	D	E	F	G	H	J	K	L	M	N	P
1.0	-	1	-	3	1	2	-	-	-	2	-	4	5	12
0.3	1	2	3	5	3	4	7	4	13	6	7	11	15	34
0.1	2	3	5	8	6	8	12	10	20	12	15	22	35	65
0.03	5	6	9	13	12	15	20	18	28	23	33	40	65	105
0.01	8	12	15	19	22	28	30	32	35	42	60	63	95	145
0.003	14	21	26	29	41	54	45	55	45	70	105	95	140	200
0.001	22	32	42	42	70	78	65	83	65	100	150	120	180	250

Other attenuations

Following attenuations are neglected in the calculations:

- **Precipitation:** caused by fog, clouds, sand and dust storms.
- **Scintillation:** A change in the direction of propagation of a radio wave, caused by refractive index changes in the transmission path. Result of temperature, humidity and pressure irregularities called atmospheric turbulence.
- **Multipath:** is when waves arrive simultaneously at a receiving antenna via several propagation paths and, by interfering with each other, give rise to (frequency-selective) fading. This effect is more significant for decreasing elevation angles due to increase of portion of the propagation path and earth proximity.
- **Wave front incoherence:** A decrease in effective antenna gain, due to phase decorrelation across the antenna aperture, caused by irregularities in the refractive-index structure. These variations are more significant with large aperture antennas.
- The total attenuation is not only a summation, see ITU-R P.618-8:
  $a_{tot} = a_{atm} + SQR((a_{rain} + a_{cloud})^2 + a_{scintillation}^2)$

Noise

Noise has a flat frequency spectrum so the noise power P_n per unit bandwidth B_n is constant.
Noise Power Spectral Density: $N_0 = P_n / B_n = k \times T$

Noise Power: $N = k \times T \times B_n$, with $B_n \approx 1.12 \times B_{3dB}$ (higher than 3dB bandwidth)

The noise factor indicates the decrease in signal-to-noise ratio (SNR) of a noisy signal (S_i plus N_i), between input and output of a noisy amplifier, when noise source is θ_0. The noisy amplifier is replaced by an ideal amplifier with gain G and an equivalent **Noise Source $N_{a,i}$** at its input:
Noise Factor: $F = SNR_i / SNR_o = (S_i / N_i) / (G \times S_i / (G \times (N_i + N_{a,i})) = 1 + N_{a,i} / N_i$

Noise Figure: $F_{[dB]} = 10 \times \log F$

When dealing with satellite sources, the source temperature will generally be much lower than θ_0, so the noise figure becomes misleading. In this case, the effective noise temperature of a noise source $N_{a,i}$ is more interesting, because it is independent of any reference.

Effective Noise Temperature: $T_{a,i} = (F - 1) \times \theta_0$
Because of the simple relation between the noise and the resistor temperature, it makes sense to define an effective noise temperature for other noise sources too, even if they are not thermal in origin, e.g. interference from another station. A noise source having a noise temperature T generates a noise power, equal to the thermal noise that would be generated by a resistor at temperature θ. For a perfect absorbing object or so-called blackbody the emanating noise is proportional to the objects' temperature.
Addition of noise temperatures of serial resistors $R_1..R_i$ depends on fractional transmissivity:
$T = \Sigma_{[i=1..i]} (T_i \times \eta_i) = \Sigma_{[i=1..i]} (T_i \times 10^{-ai/10})$

Antenna noise temperature T_{ant}

Antenna Noise consists of ground-, atmospherical-, rain- and cosmic backgound noise. Neglected is galactic noise, that dominates background noise for frequencies below 4GHz and solar noise when tracking near the sun. Note that the increase in noise temperature due to precipitation affects only the antenna temperature of earth station antennas. The satellites' antenna always looks at the hot earth of about θ_0.

Ground noise increases if the feed over-illuminates the dish and catches backscatter from the warm ground and from reflections e.g. of the feed assembly.
Approximation formula for ground noise temperature: $T_{gnd} \approx 15 + (30/d) + (180/\varphi_{el})$, [2]

Cosmic noise: $T_{cos} \approx$ 1.7K at 1.7...2.3GHz, 2.5K at 8.4GHz, 2.0K at 32GHz

In general the atmospheric effective temperature θ_{atm} depends upon frequency and attenuation through the physical processes that produce the attenuation. For attenuation values less than 6dB and frequencies below 50GHz it can be approximated, with a weak dependence on frequency (265K in the 10-15GHz range and 270K in the 30GHz range). When surface temperature is known, a first estimation can be also obtained by multiplying the surface temperature by 0.95 in the 20GHz band and by 0.94 for the 30GHz window: $\theta_{atm} \approx 0.95 \times \theta$, [3]

An attenuating atmosphere creates an **Atmospheric Noise Temperature:** $T_{atm} = \theta_{atm} \times (1 - \eta_{atm}) \approx 40K$

Here we define the **Nominal Antenna Noise Temperature** without ground and cosmic noise, only with an attenuating atmosphere. Manufacturers may use other definitions.

$T_{ant,nom} = T_{atm}$

$T_{ant,cs} = T_{gnd} + \theta_{atm} \times (1 - \eta_{atm}) + T_{cos} \times \eta_{atm}$

$T_{ant} = T_{gnd} + \theta_{atm} \times (1 - \eta_{atm} \times \eta_{rain}) + T_{cos} \times \eta_{atm} \times \eta_{rain}$

System noise temperature T_{sys}

consists of LNB-, feed- and antenna noise temperature. The influence of the IRD on the system noise can be neglected, cause noise of first amplifier (LNB) prevails if it has a great amplification.

Radiation efficiency $\eta_{rad,rx}$ in receiving direction includes all attenuating components of the feed system. It decreases the **Antenna Noise Temperature** ($T_{ant} \times \eta_{rad,rx}$) but, unfortunately much more important, it adds a **Feed Noise Temperature** $\theta \times (1 - \eta_{rad,rx})$. Therefor it's very important to keep the feed attenuation low in the receiving path by using short waveguides to the LNB.

LNB noise temperature is calculated with θ_0 by definition: $T_{lnb} = \theta_0 \times (10^{Flnb[dB]/10} - 1)$

$T_{sys,nom} = T_{ant,nom} \times \eta_{rad,rx} + \theta_0 \times (1 - \eta_{rad,rx}) + T_{lnb}$

$T_{sys,cs} = T_{ant,cs} \times \eta_{rad,rx} + \theta \times (1 - \eta_{rad,rx}) + T_{lnb}$

$T_{sys} = T_{ant} \times \eta_{rad,rx} + \theta \times (1 - \eta_{rad,rx}) + T_{lnb}$

Downlink degradation DND caused by rain: $DND = a_{rain} + 10 \times \log(T_{sys} / T_{sys,cs})$

Literature

1. Bisante Consortium: GEO Satellite Network Characteristics
2. http://photos.imageevent.com/qdf_files/technicalgoodies/training/GT.doc.pdf
3. ITU-R P.1322, Radiometric estimation of atmospheric attenuation