The ladybird guides

Book II

Day 7 - Reception

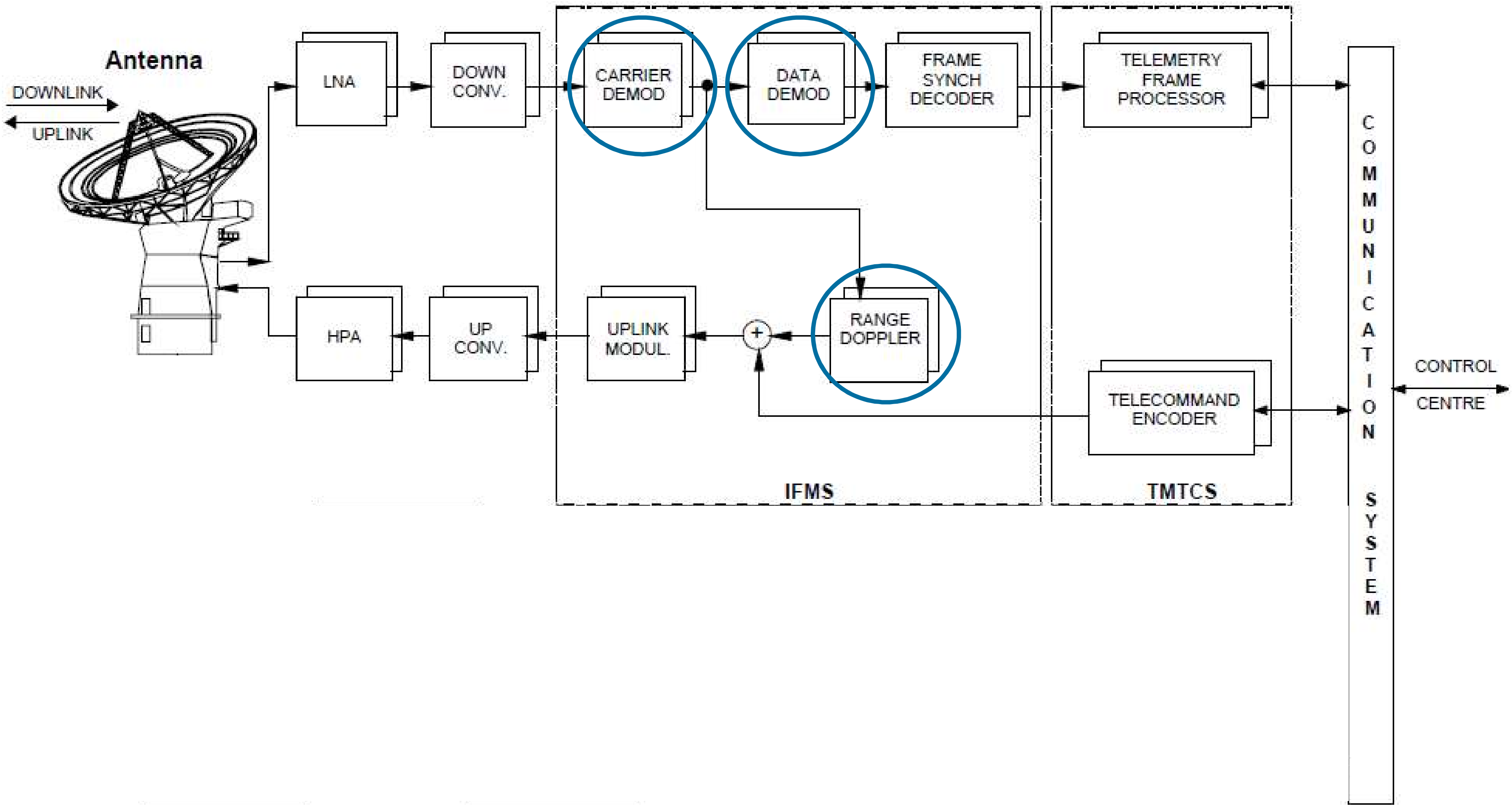
Day 7: Link Budgets: Reception

Objective:
To appreciate the different criteria to be fulfilled before the link will close
To understand the nature of noise
To appreciate G/T as an extremely useful measurement

1. Signal to noise at the receiver
2. What is noise and how do we calculate it?
3. Carrier Recovery
4. Data Recovery
5. G/T something we can measure at last
6. Other important aspects of ground stations

System temperature

We measured the received power arriving in our system. Now we have to share it between…..

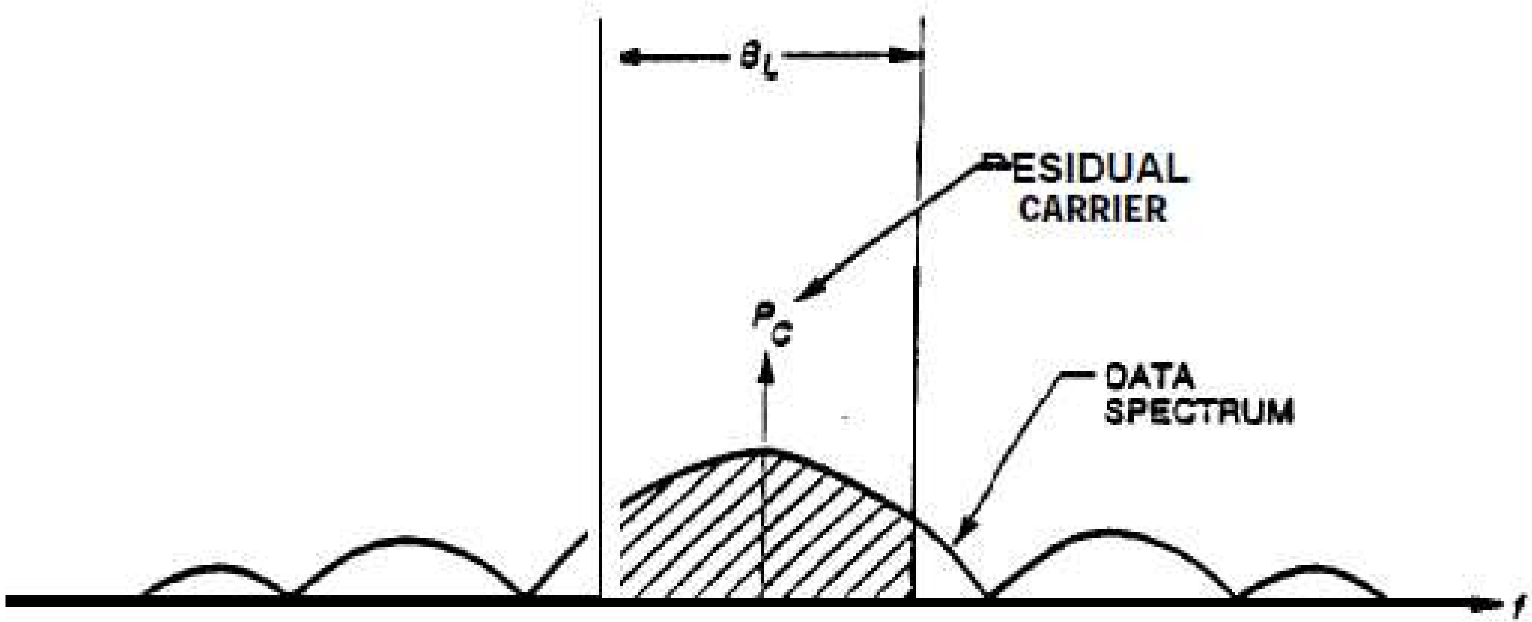


L

Recap: Carrier Recovery with residual carrier

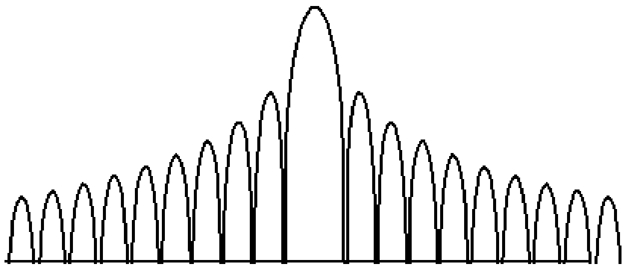
The carrier signal needs to be a certain amount of times stronger than the combined noise in the PLL bandwidth otherwise the PLL loop cannot track it.

We need at least 10dB for TC and downlink tracking and 17dB for telemetry.



Recap: Carrier recovery with suppressed carrier

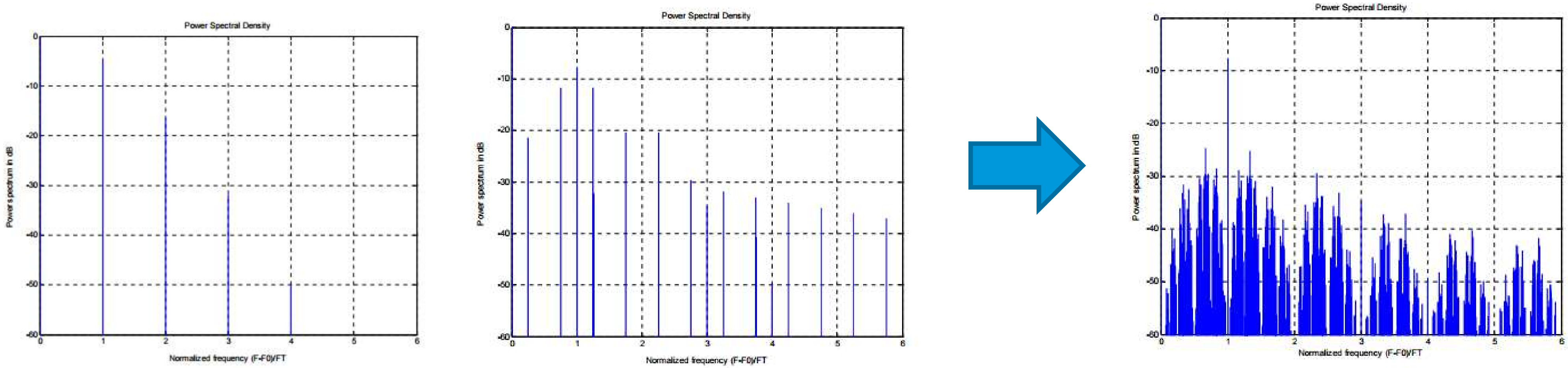
As noted earlier, if we use direct modulation with a modulation index of +/- Π rad for BPSK (or any other higher modulation scheme) we will totally suppress the carrier signal.



The most poplar technique to recover the carrier signal when it has been totally suppressed is the Costa's loop.

As the Costa's loop squares the noise we have to account for a x4 loss in power (6dB) if we want to use it.

Recap: Ranging with subcarriers



Ranging works by measuring the phase difference between the sine wave modulated on the subcarrier and the received subcarrier.

Subcarriers remove energy from the carrier!

This has to be accounted for in the link budget.

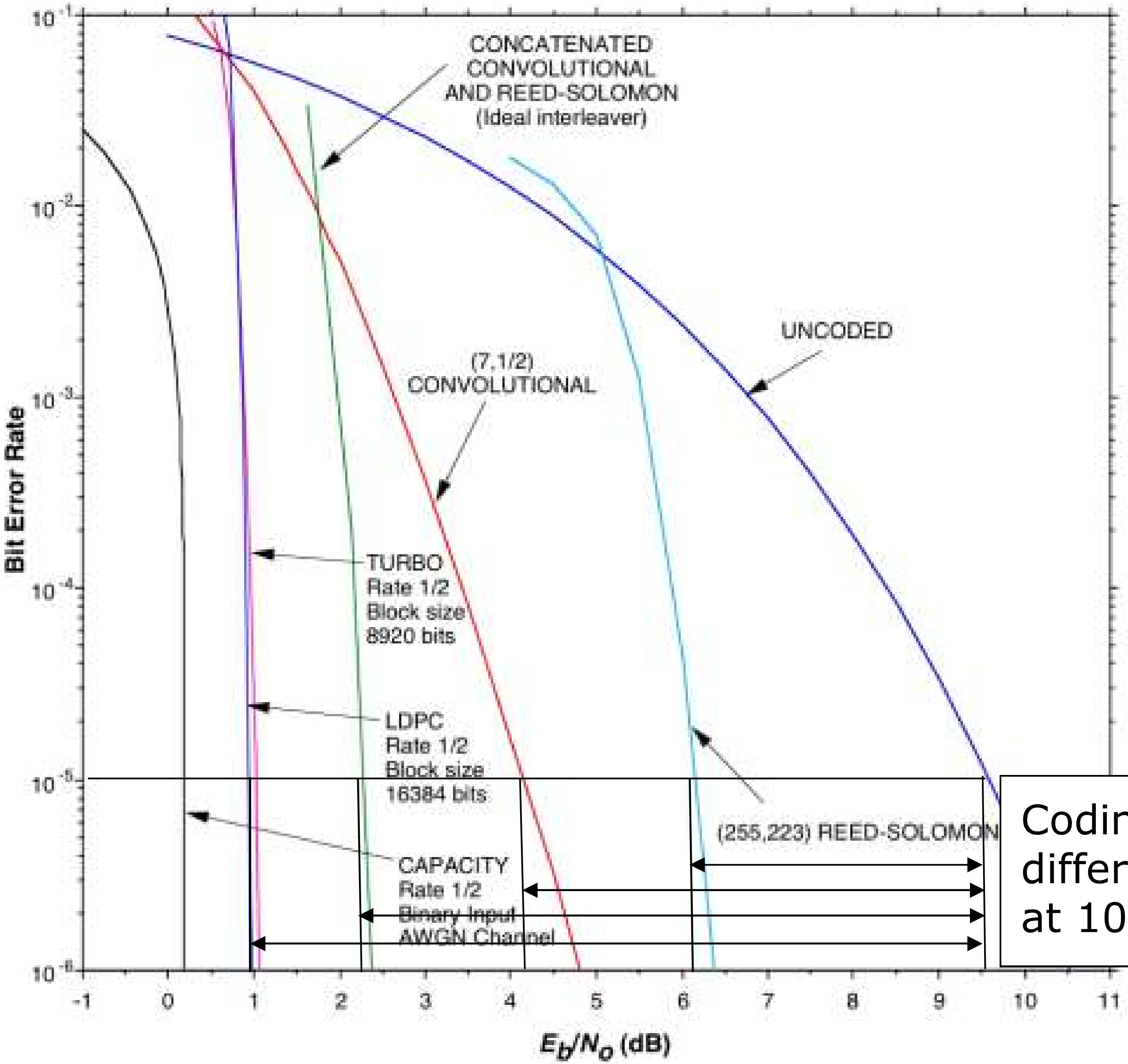
Recap: Bit Lock and the DTTL loop

Remember noise is like a stormy sea, we need to know how high the rock stands ***above the sea level*** in order to calculate how often it will be submerged.

We use the term Energy per bit/Noise Density (Eb/No) to describe the height of the rock above the waves.

Recap: Acceptable BER versus Eb/No

High error rate



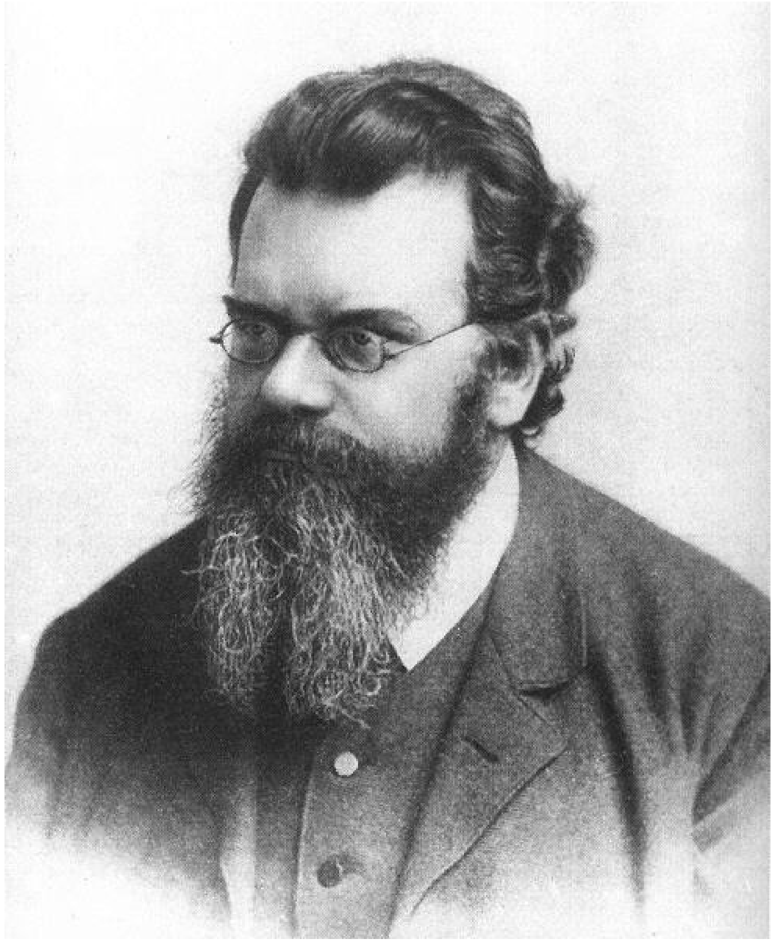
Low error rate

Eb ✓

No ?

Coding gains for different schemes at 10^{-5} BER

Quiz



1844 - 1906

Austrian Physicist and Philosopher

Taught at University of Graz

Developed the statistical concept of nature connecting atom behavior and substance properties

Remarkable considering not many people even believed in atoms back then!

Explains

- the second law of thermodynamics
- our concept of time?
- temperature

His famous constant is very useful for space communications

Quiz

Quiz: What is this lady doing?

The lady is listening to the static in a metal bar through an amplifier.

What does she hear?

What happens when she heats the bar?

What happens when she cools the bar?

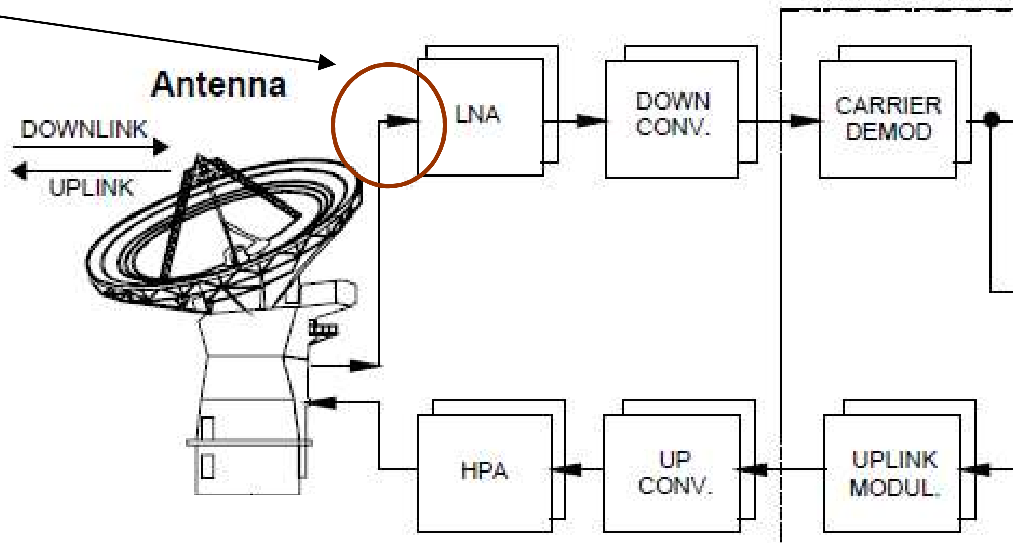
Metal contains free electrons that speed up as the temperature rises. As they move they release electromagnetic radiation.

The random electromagnetic energy produced by moving electrons (i.e. noise) is related to temperature.

System temperature

The amount of noise in our system is called the system temperature

It is measured at the input to the LNA



It is the sum of all the physical temperatures inputting noise to the LNA.

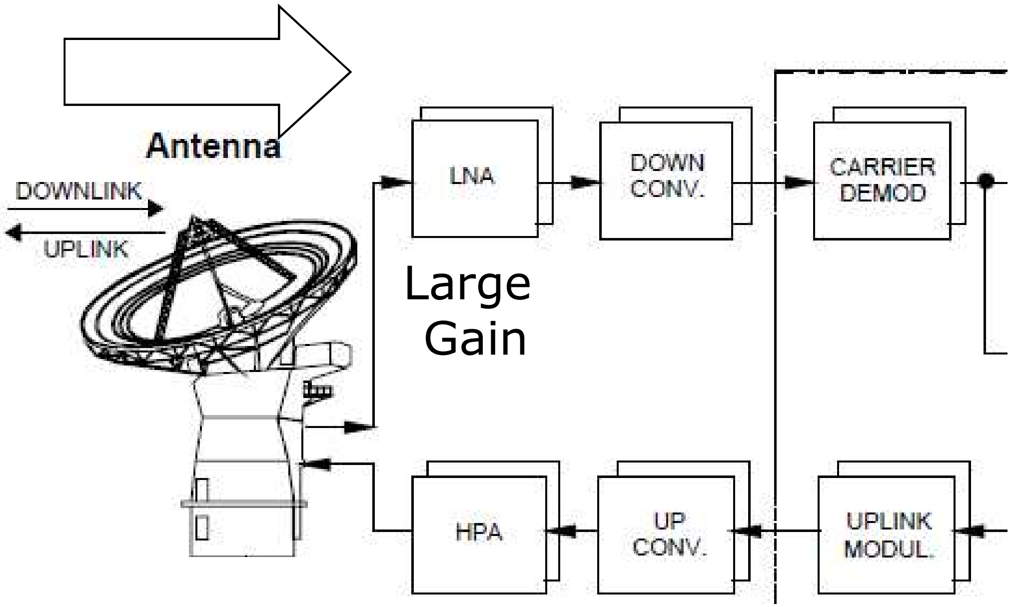
For the LNA itself the Noise Figure [dB] is related to the actual output noise divided by the output noise of an ideal amplifier.

System temperature

It is calculated by taking all the other equipment temperatures and multiplying or dividing their contribution through the amplifiers depending on the direction.

Since the LNA has a very large gain any noise from the LNA itself, the waveguides and the antenna gets multiplied enormously.

Hence these are the most sensitive parts of the system to temperature.



Noise from the waveguide and LNA

We can cool down the LNA using cryogenics (liquid helium). We can usually get to 50K (-220 °C) system temperature using active cryogenic cooling equipment and isolation. This is rather difficult, if at the same time there is high power radiating equipment next to it!!

NASA get even lower system temperatures due to the fact that they cryogenically cool their waveguides as well.

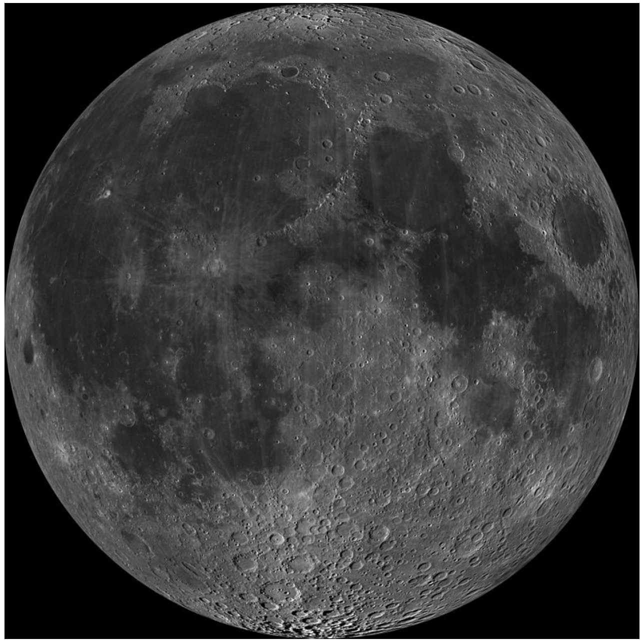
For those missions without cryogenic cooling, it still shows the advantages of good thermal insulation and air conditioning vis a vis reception performance.

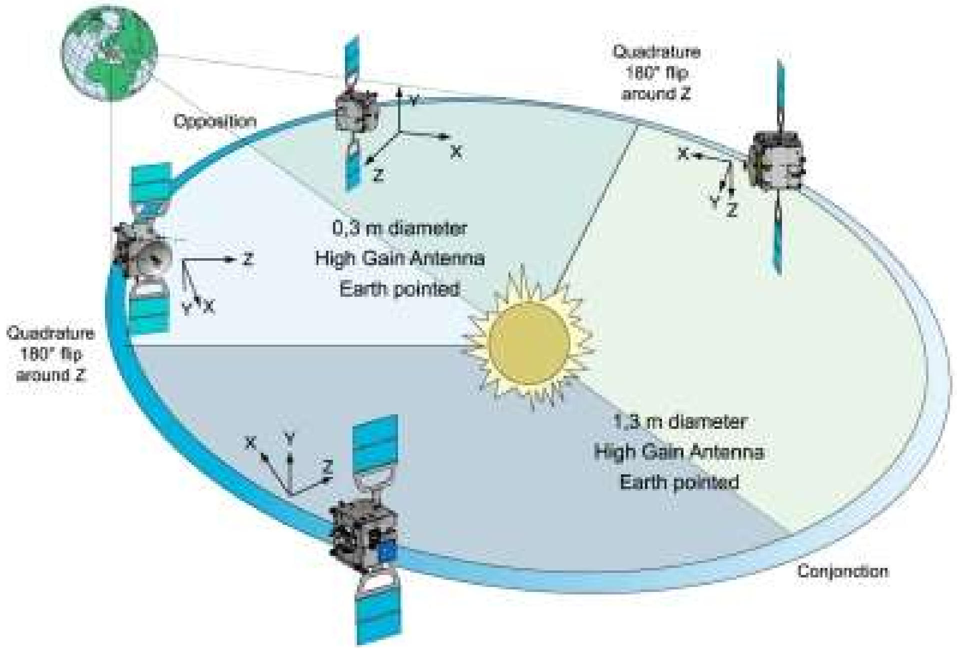
ESA uses cryo LNAs in all 35m stations and Kourou Dianne for X band.

Remember the LNA in Latvia?

Noise coming in from the antenna

As well as atmosphere and ground what else might contribute to antenna temperature?





Objects (like the sun or moon) inside the field of view will raise the system temperature.

$$\text{Temperature to add} = \text{physical temperature of object} * \frac{\text{solid angle object}}{\text{solid angle beam width}}$$

Impact on interplanetary missions in opposition and conjunction phases due to the sun..

RECAP: The challenges…

Note in the spacecraft the receiving equipment is usually around room temperature (290K; 20 °C).

So typical spacecraft values for system temperature are in the region of 450 to 550 K.

Spacecraft TXs and RXs

Low power
"Hot"
Limited processing
Limited size

System Temperature

How does calculating system temperature help us calculate Noise?

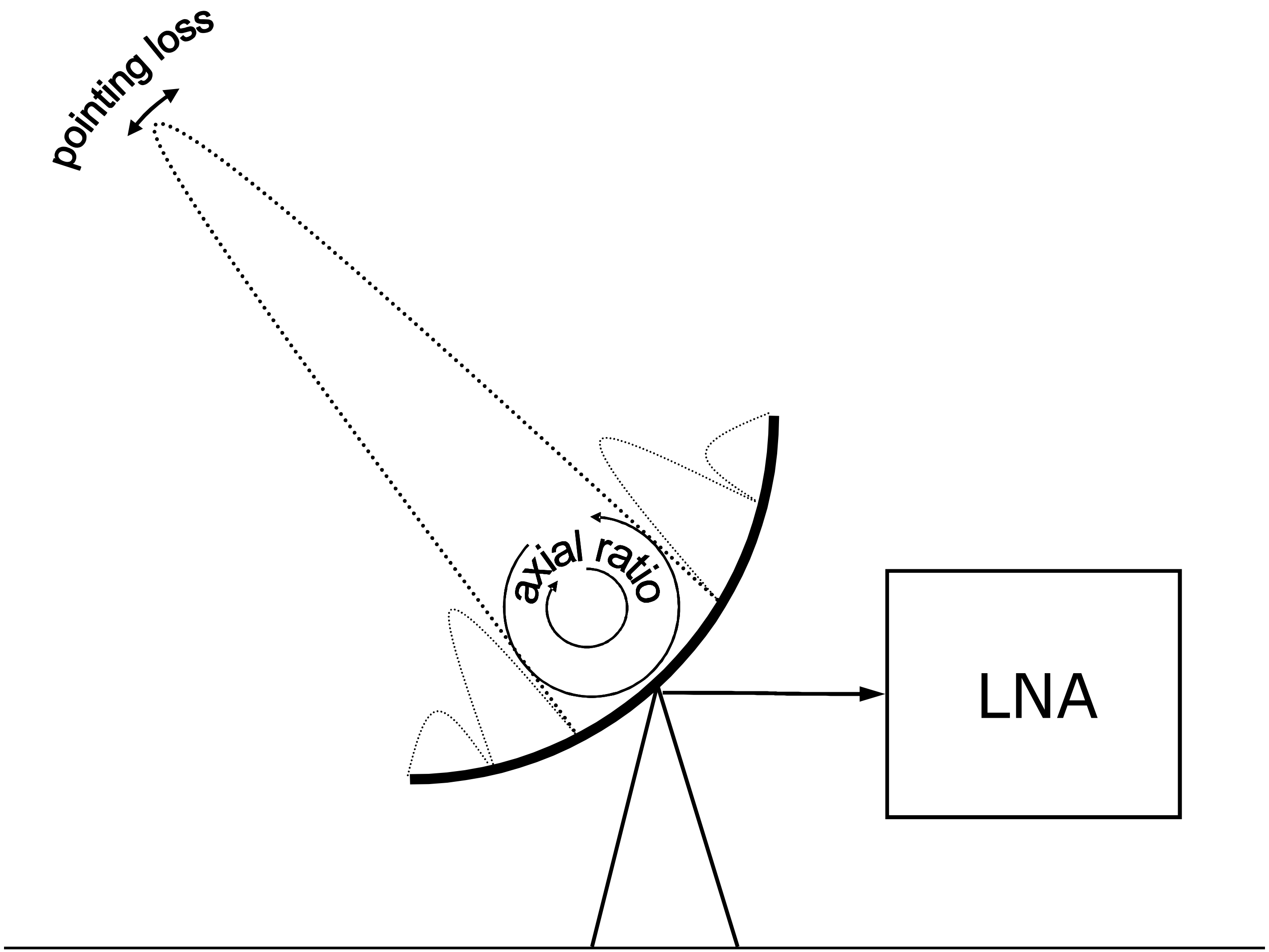
Thanks to Ludwig Boltzmann, we have the equation to simply relate the two:

Noise Density (W/Hz) = k x System Temperature

Where k = Boltzmann's constant = 1.38×10^{-23} J/K

Note that k is usually expressed as dBW = 10 Log(1.38*10E-23) = -228.6 dBW/K-Hz in the calculations (adding is easier than multiplying)..

Ground Station Reception Losses



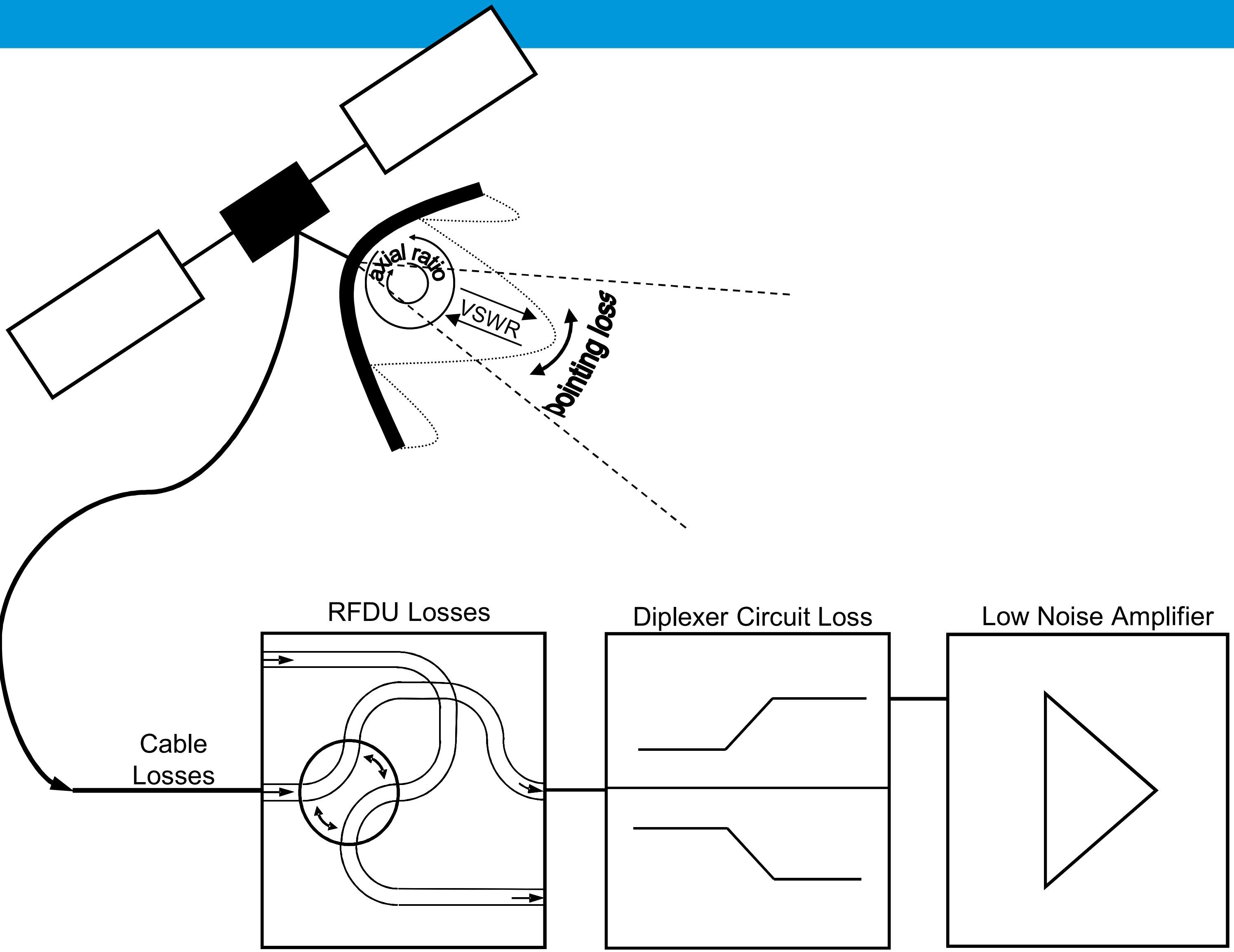
Ground Station Reception Losses

- Pointing loss [dB]

Note: Polarisation losses are omitted here

(can only be calculated by taking into account axial ratios of both antennas)

Spacecraft reception losses



Satellite Reception losses

- Diplexer Loss [dB]
- RFDU Circuit Loss [dB]
- Cable Loss [dB]
- VSWR Loss [dB]
- Pointing Loss [dB]

= Satellite Receive Losses

Note: Polarisation losses are omitted here (can only be calculated by taking into account axial ratios of both antennas)

Calculating receive power using the classic equation

Received Power = EIRP - FSPL – (Transmission + Receive Losses) + Receive antenna gain

Now can you see why FSPL is so useful?

Great, but it sounds hard to do in practise

Yes, this is correct, but there is a REAL measurement we can make that will combine the entire receive system losses, gains and noise into one figure.

It is called

G/T

It is literally the (Antenna Gain – Receive losses) divided by System Temperature and is a measurement of system performance that is directly proportional to signal/noise ratio.

Great, but it sounds hard to do in practise

To measure G/T we can do a real field measurement!

We measure the noise power of the system when the antenna is pointing at the sun and compare it to when it points at an area of cold sky.

This gives us what is known as the Y factor.

$$Y = P_{sun/} P_{cold\_sky}$$

$$G/T = \frac{(Y-1).8\,\pi\,.k.L}{F.\,\lambda^2}$$

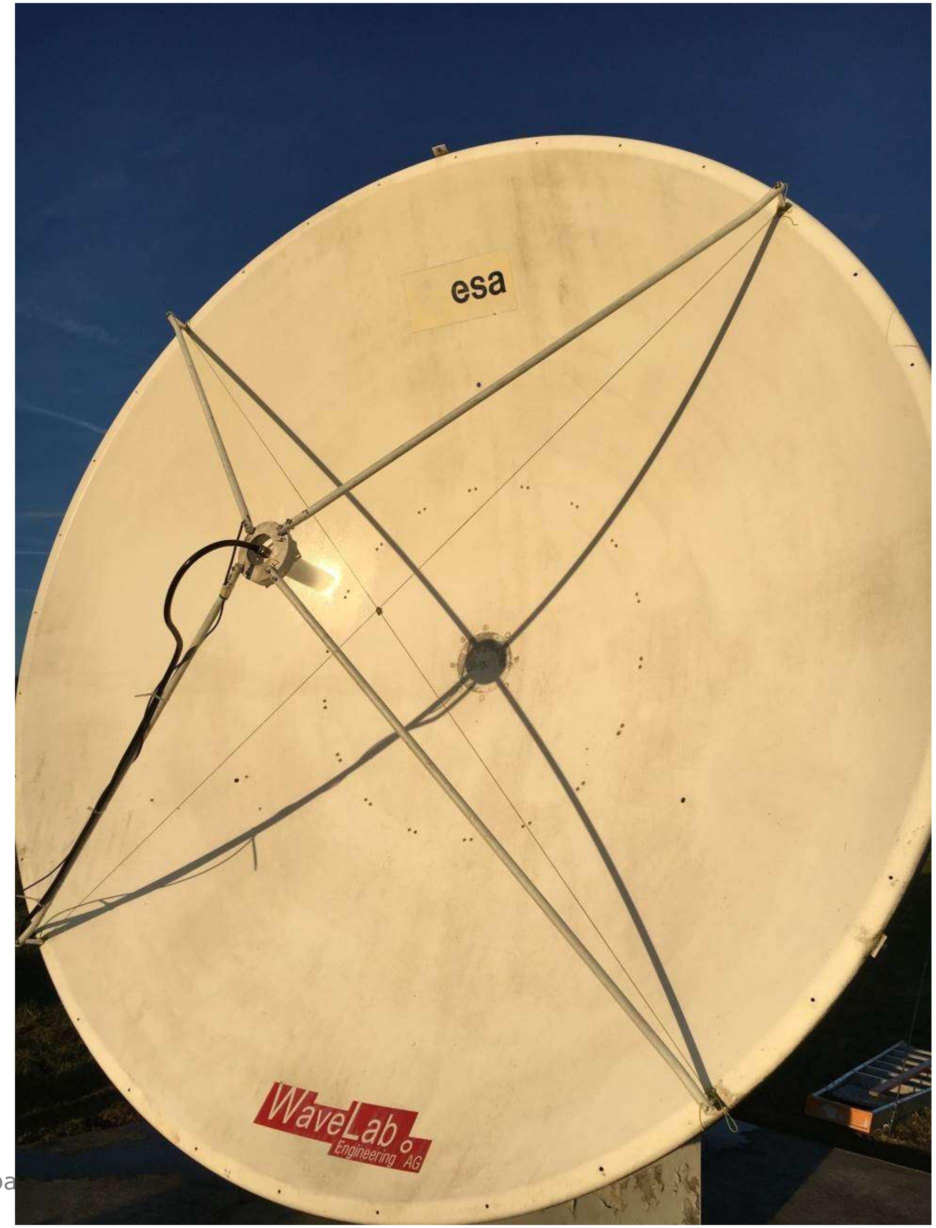
Where k = Boltzmann's constant,

F = Solar flux at operating frequency [W/m2/Hz],

L = Beam size correction factor,

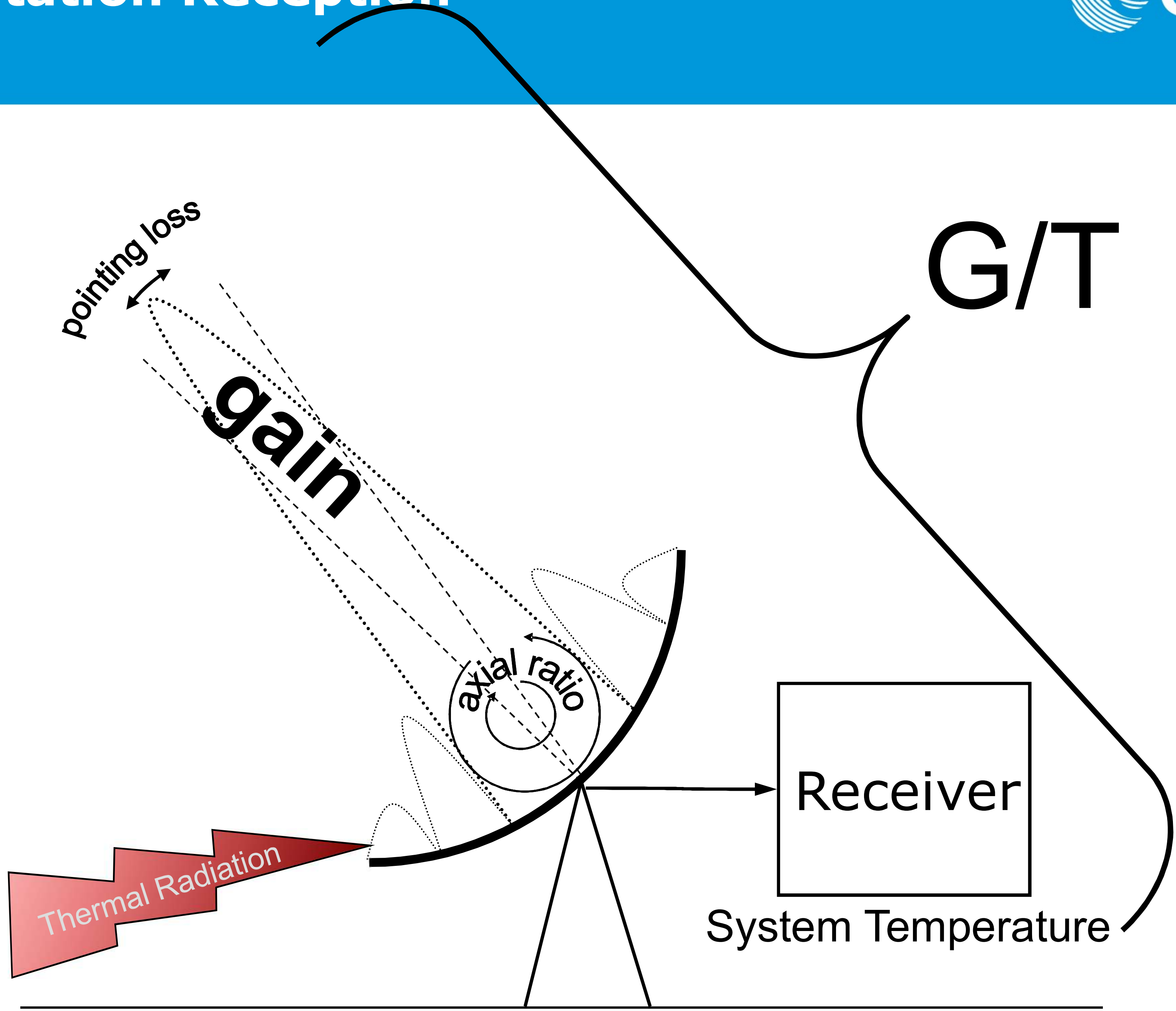
λ = wavelength in m (at operating frequency)

When the invisible becomes visible

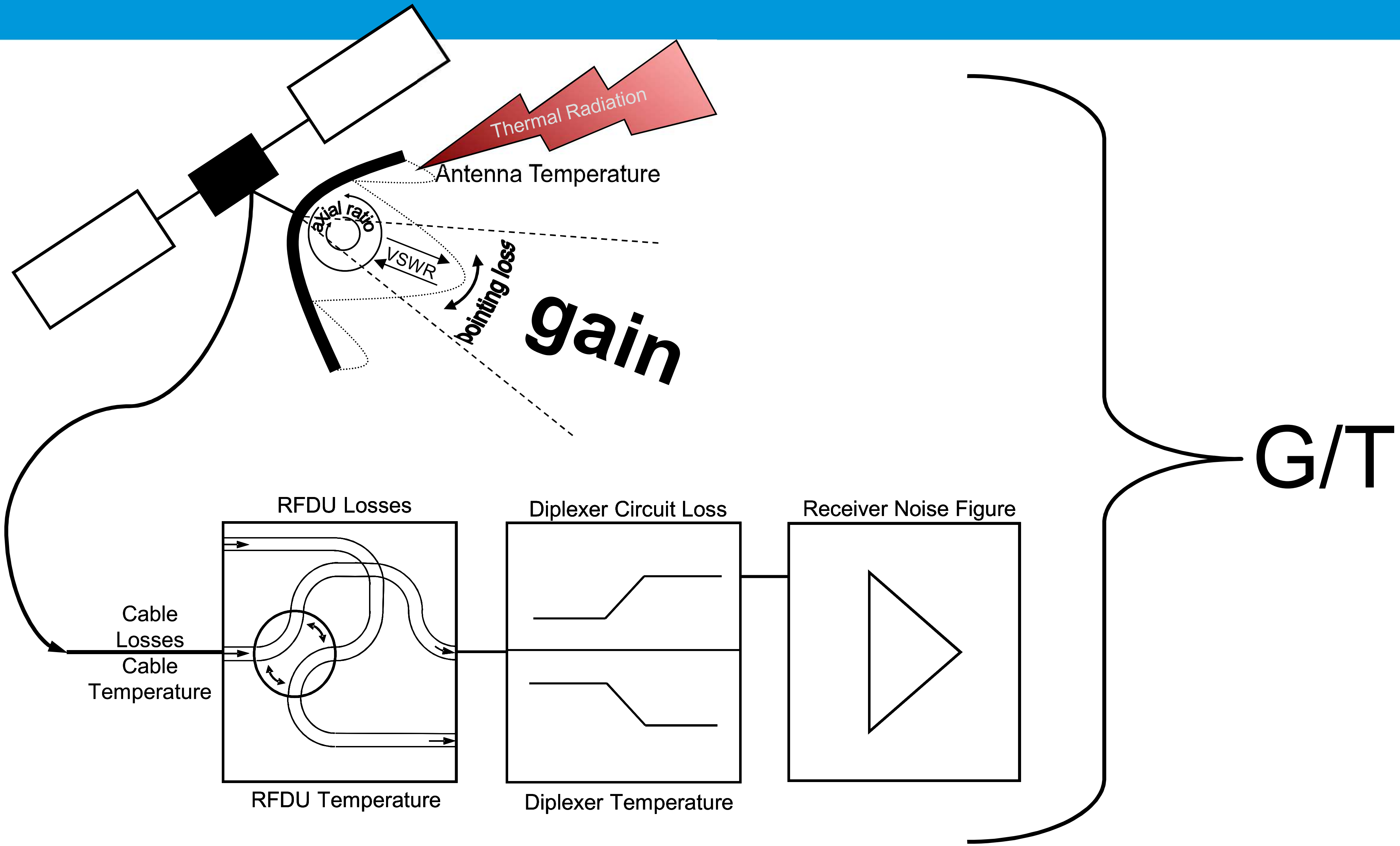


Redu 4 during the sun pointing part of the G/T measurement

Courtesy of Etienne Tilmans, ESA/Redu


pointing loss
gain
axial ratio
G/T
Receiver
System Temperature
Thermal Radiation

Spacecraft Reception



G/T Calculation

+ Gain [dBi]

- Pointing loss [dB]

- System temperature [dBK]

= G/T [dB/K]

Note: Polarisation losses are omitted here (can only be calculated by taking into account axial ratios of both antennas)

Signal/Noise Calculation

The beauty of G/T is that it can go straight into a calculation with EIRP to calculate Received Power/No directly

+ EIRP [dBW]
- (Atmospheric + Ionospheric Loss) [dB]
- Free Space loss [dB]
+ G/T [dB/K]
+ 228.6 [dBW/Hz] (Boltzmann constant = noise power within 1 Hz bandwidth)
= Received Power/No [dB/Hz]

This value is more commonly referred to as the signal to noise ratio **S/No**. It gives the power of the received signal relative to the noise within 1 Hz bandwidth.

Carrier Recovery in PLL loop

Recap: we want to make sure the signal/noise ratio within the PLL bandwidth is large enough for the PLL to track the carrier.

Noise in PLL loop = No x PLL bandwidth

$$\text{Therefore S/N (PLL loop)} = \frac{\text{Power in Carrier}}{\text{No x PLL bandwidth}}$$

We need at least 10dB for TC and downlink tracking and 17dB for telemetry.

Power in carrier with residual carrier

This loss will depend on

1. Pulse shape chosen
2. Modulation index chosen (closer to +/-π the more loss due to carrier suppression)

For a square wave pulse:

Power in Carrier = Received Power. cos2(modulation index)

For a sine wave pulse:

Power in Carrier = Received Power. J^2_0(modulation index)

Where J_0 is a Bessel function.

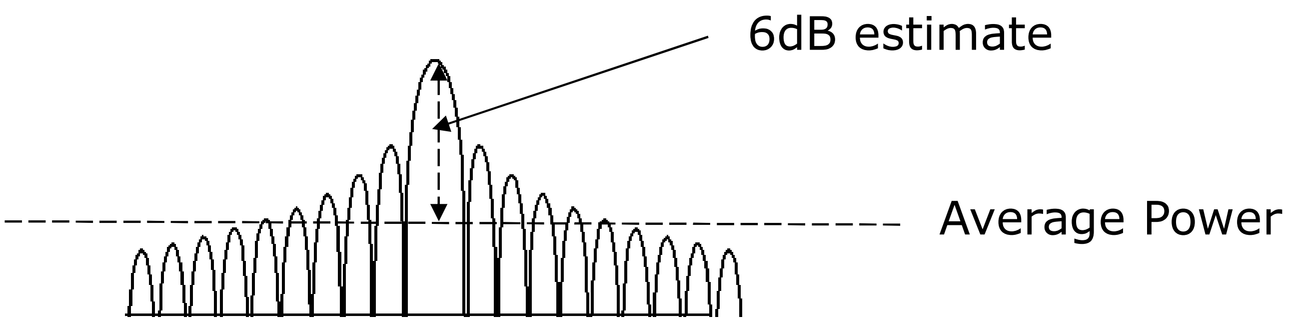
Note that this shows the importance of the pulse shape chosen, in the signal/noise calculations as well as bandwidth usage calculations

Also note if other forms of modulation occur on the signal (e.g. ranging) these need to be taken into account in these equations.

Power in carrier with suppressed carrier

If the modulation index is +/-п then we do not have a carrier. We have to work out the average power (i.e. received power/total bandwidth) and then we add 6dB to account for the “hill” shape of the power density profile.

$$\text{Carrier power} = \frac{\text{received power}}{\text{total 99\% bandwidth}} + 6\text{dB}$$



$$\text{Therefore S/N (PLL loop)} = \frac{\text{Received Power/Total Bandwidth} + 6\text{dB}}{\text{No x PLL bandwidth}}$$

Data Recovery

Recap: we want to make sure that the energy per bit / noise density ratio is enough for the BER and coding scheme selected.

Noise density = No

$$\text{Power for each bit} = \frac{\text{Received Power} - \text{Power in Carrier} - \text{Power for ranging}}{\text{TC/TM data rate}}$$

$$\text{Therefore } Eb/No = \frac{\text{Received Power} - \text{Power in Carrier} - \text{Power for ranging}}{\text{No} \times \text{TC/TM data rate}}$$

Carrier Recovery Calculation using dBs

+ S/No [dB/Hz]
- Carrier suppression [dB] (depends on modulation index, 6dB for suppressed carrier and Costas loop)
- Ranging loss [dB]
- PLL bandwidth [dBHz]
- 17 [dB] (required Carrier to Noise ratio for stable carrier tracking for TM signal); 10 [dB] for TC signal)

= Carrier margin [dB]

(minimum margin required: 3 dB)

Warning: Be careful with PLL bandwidth. B_w and B_L are used:.

Therefore PLL bandwidth = $B_w = 2B_L$

Also note that some spacecraft transponders allow it to be changed based on the received power and many ground stations have different settings for it that can be chosen – remember the Huygens problem!

Telemetry Reception Calculation using dBs

\+ S/No [dB/Hz]

\- Carrier power [dB] (portion of received power allocated to carrier recovery)

\- Ranging power [dB] (portion of received power allocated to ranging subcarriers)

\- Bit rate [dBHz]

\- required Eb/No for coding scheme and BER chosen [dB]

= Telemetry margin [dB]

(minimum margin required: 3 dB)

Power Flux density

The PFD limit is given within any 4 kHz band width, thus a modulation with residual carrier has more problems (as it has a peak).

For suppressed carrier systems we simply take the carrier power as defined by

$$\text{Carrier power} = \frac{\text{received power}}{\text{total 99\% bandwidth}} + 6\text{dB}$$

and divide by 4 kHz.

For residual carrier schemes, we take the carrier power as defined by

Carrier Power = Received Power x Loss due to carrier suppression

WARNING: Always calculate PFD using a elevation angle of 90 degs i.e. the spacecraft is directly above you. This is the worst case for PFD and the best for the link budget.

Link budgets

Essentially we just completed a link budget that…

1. Guarantees that (Carrier Power/Noise) is high enough so that the PLL loop can work correctly
2. Check that the PLL bandwidth is large enough to cope with Doppler changes, jitter on local oscillators and unexpected problem
3. Guarantees we have enough power to range
4. Guarantees that (Energy per bit/Noise density) is high enough so that the DTTL can recognise symbols correctly according to the desired BER
5. Guarantees that Power Flux Density Limits are not exceeded
6. Checks that the bandwidth allocation is not exceeded