Ingegneria delle Telecomunicazioni

Satellite Communications

9. Balancing Resources – Accurate Link Budget

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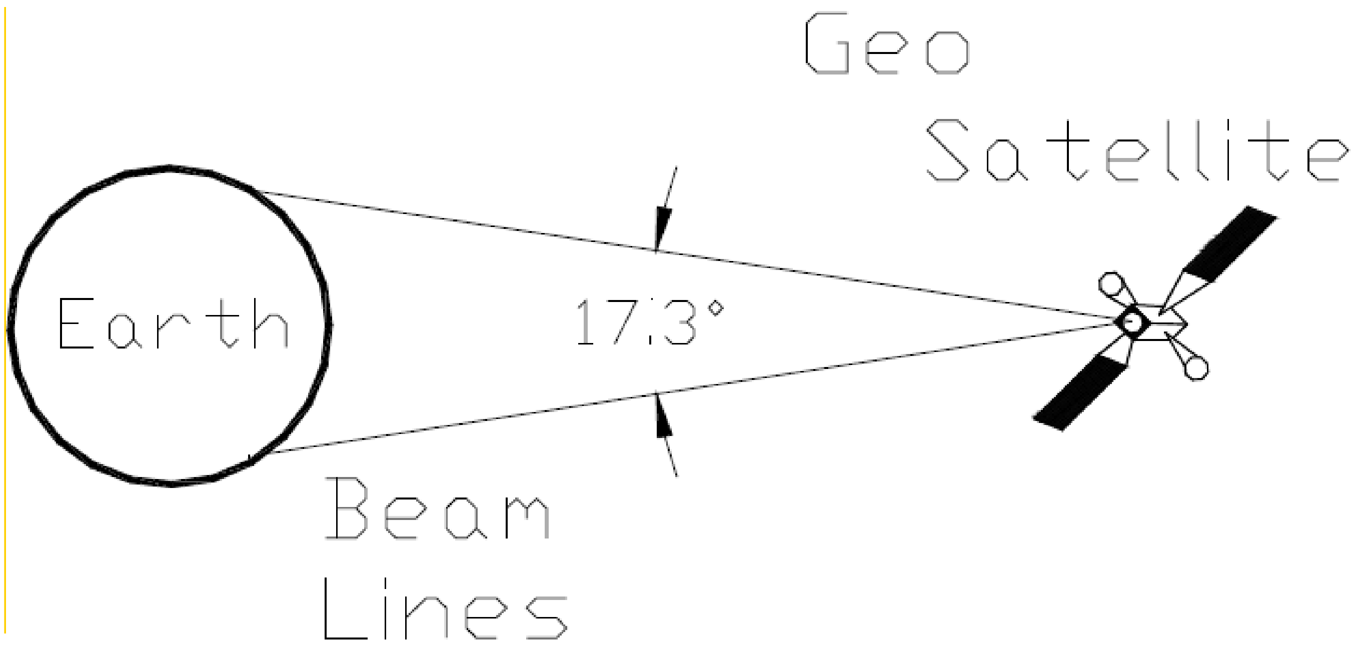
It's very far !

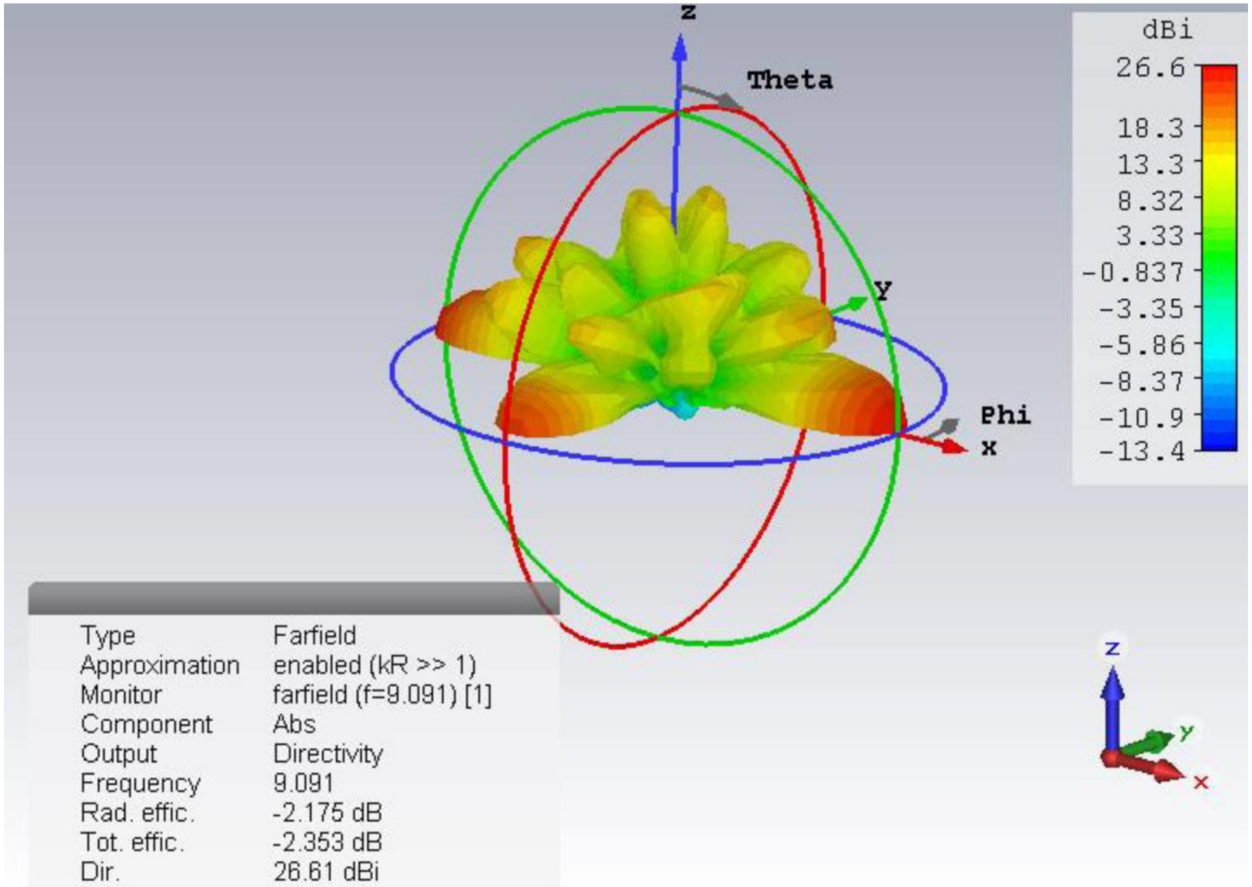


Does the satellite signal get to Earth loud enough (and vice-versa?)

What is the key factor?

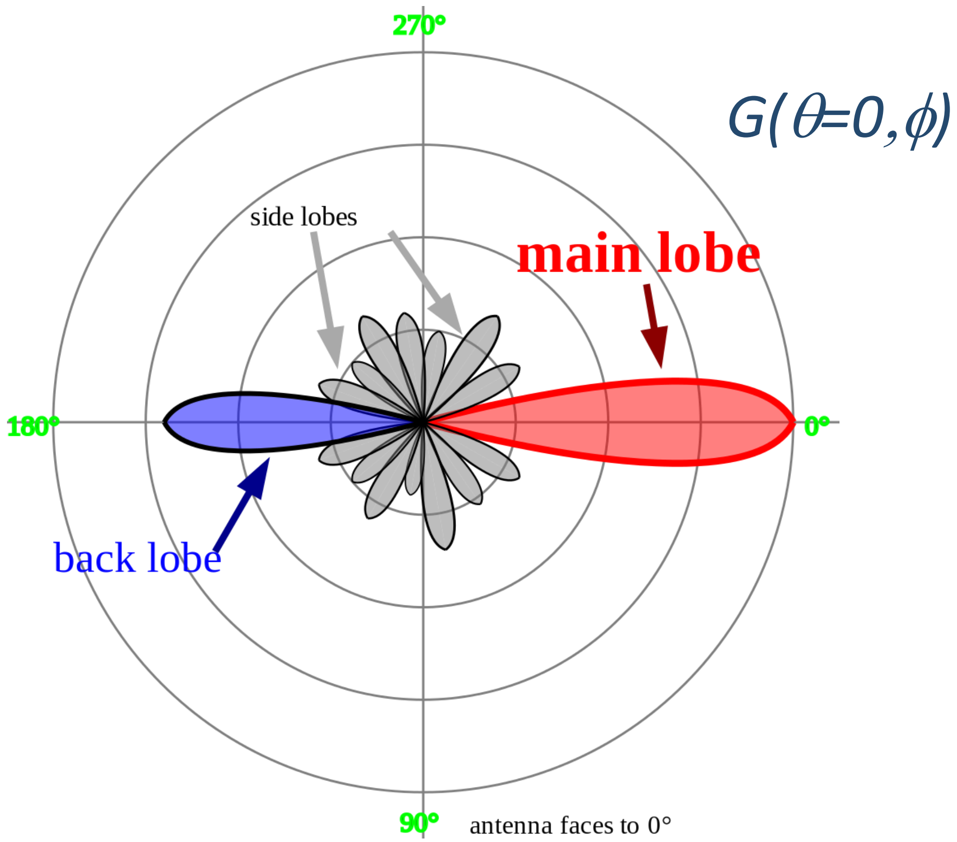
Antenna Radiation Pattern 1/3

$G(\theta,\phi)$ describes the intensity of the far field radiated by the antenna as the angle of view changes: ϕ on the horizontal plane (azimuth), θ on the vertical plane (elevation)



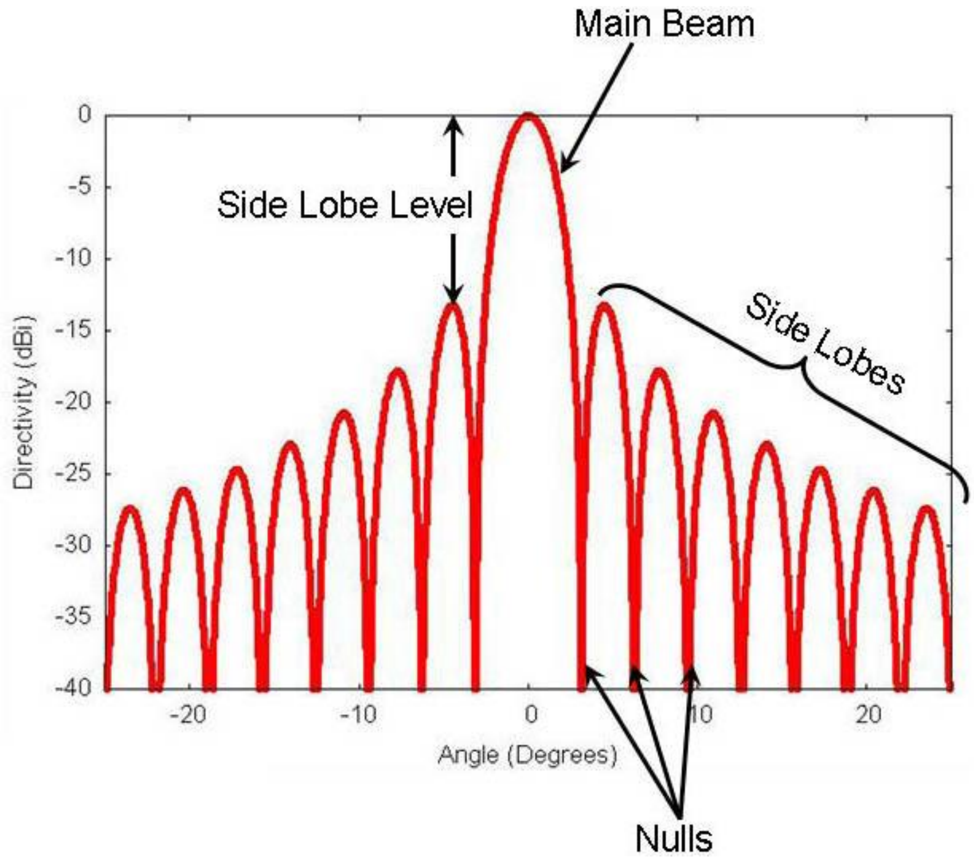
Antenna Radiation Pattern 2/3

Usually we just use (represent) a cut of the pattern on either the H o the V plan, represented on a polar chart:

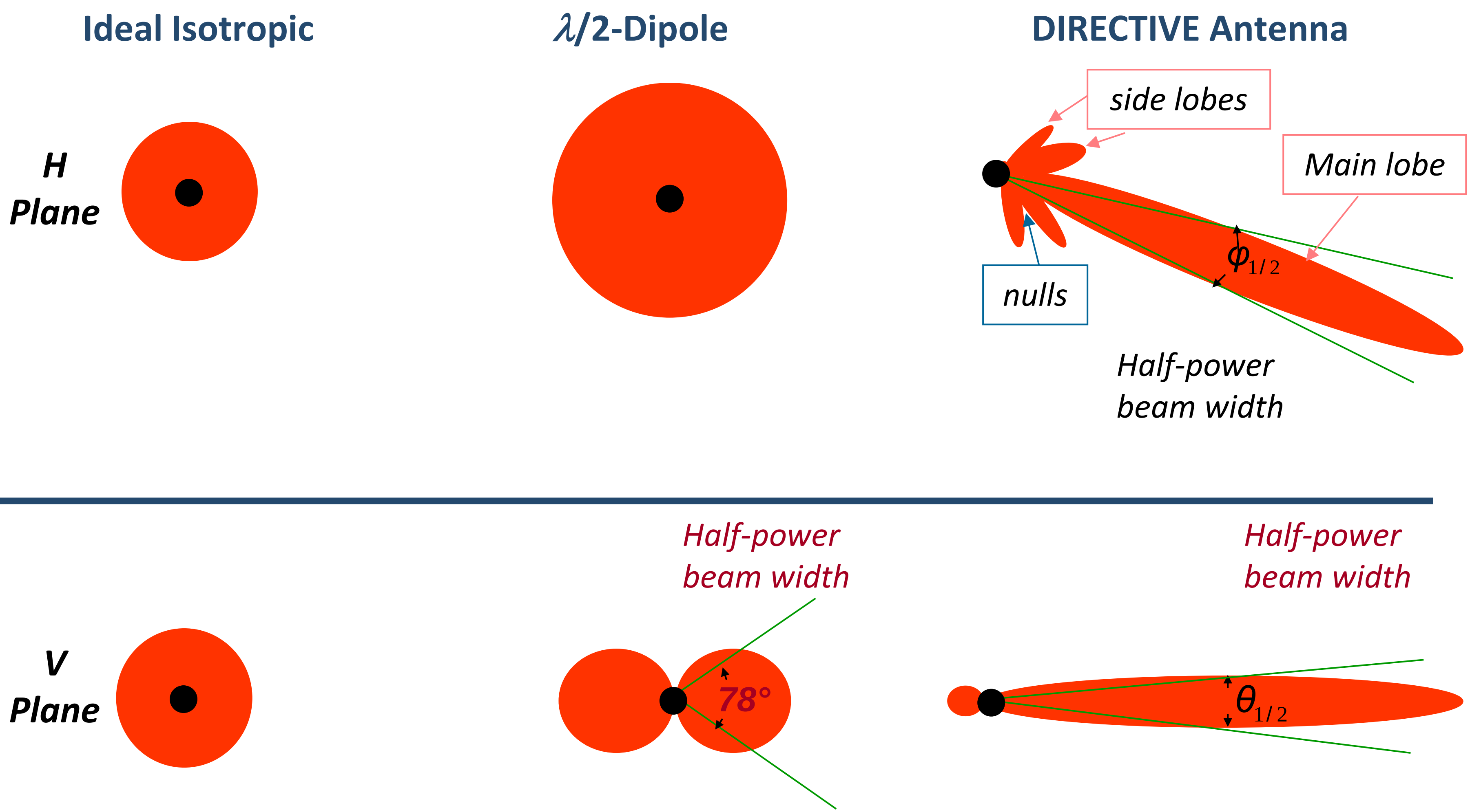


Antenna Radiation Pattern 3/3

- We can also plot the same cut $G(0,\phi)$ as a function of ϕ on a Cartesian rather than polar chart



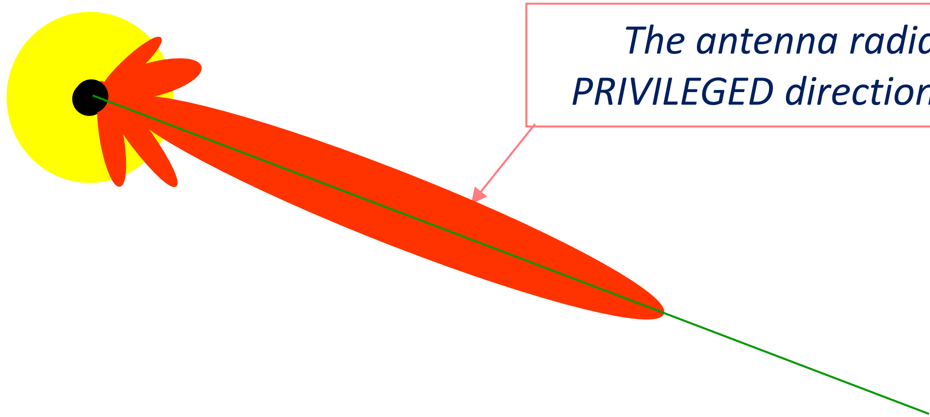
Examples


Ideal Isotropic
λ/2-Dipole
DIRECTIVE Antenna
H Plane
side lobes
Main lobe
nulls
$\varphi_{1/2}$
Half-power beam width
V Plane
Half-power beam width
78°
Half-power beam width
$\theta_{1/2}$

Antenna Gain

During *transmission*, the radiation pattern determines the ***gain*** of the antenna in a certain direction of radiation, i.e., the measure of how much in that direction the radiated power at distance *r* (or, the power flux *S* per unit area) is greater than that of an ideal isotropic antenna:

$$S(\theta,\phi;r) = G_T(\theta,\phi)\frac{P_T}{4\pi r^2}$$

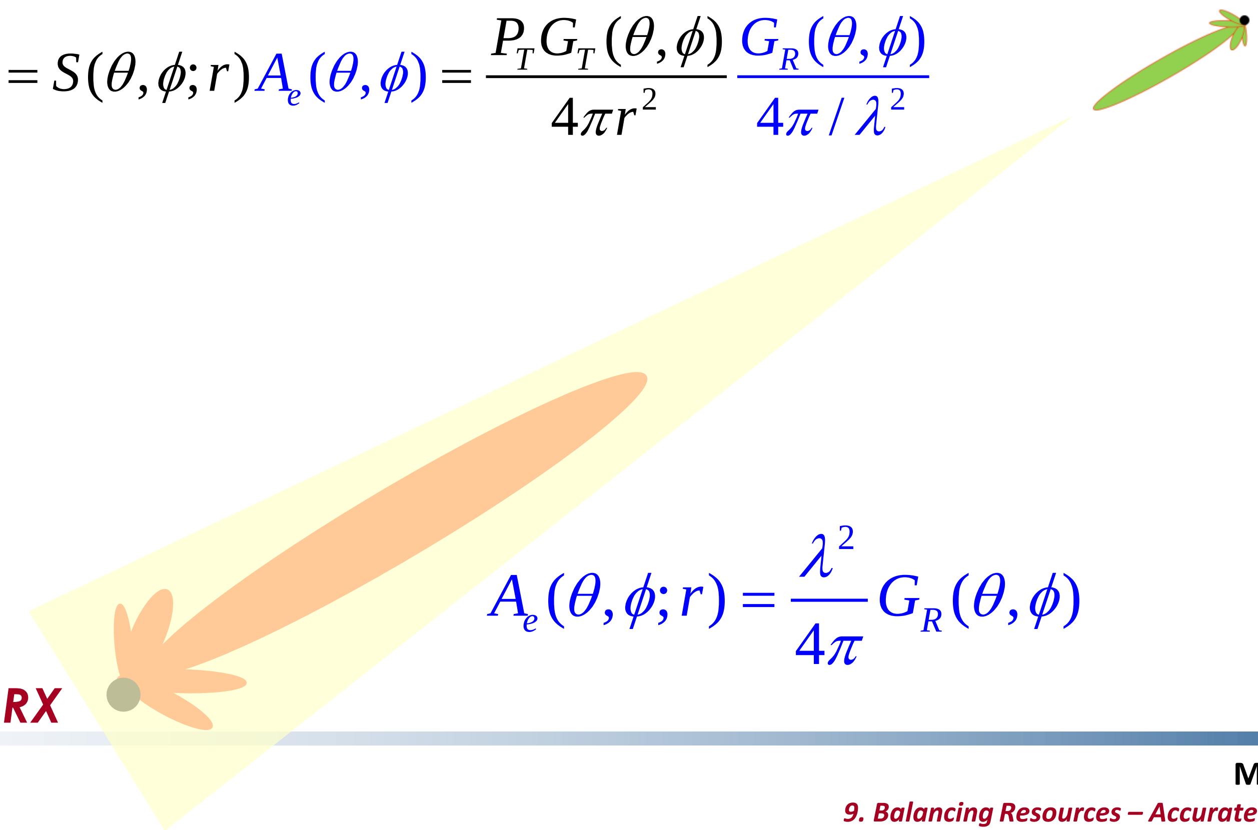


The antenna radiates towards a PRIVILEGED direction: it is directional!

Effective Area

Reciprocally, the radiation pattern establishes the directivity of the antenna in *reception* through the concept of ***equivalent area***, i.e., the measurement of how much power the antenna is able to collect in the main direction with respect to that collected by an ideal isotropic antenna:

$$P_R(\theta,\phi;r) = S(\theta,\phi;r)A_e(\theta,\phi) = \frac{P_T G_T(\theta,\phi)}{4\pi r^2}\frac{G_R(\theta,\phi)}{4\pi/\lambda^2}$$



$$A_e(\theta,\phi;r) = \frac{\lambda^2}{4\pi}G_R(\theta,\phi)$$

Example: Parabolic Antenna

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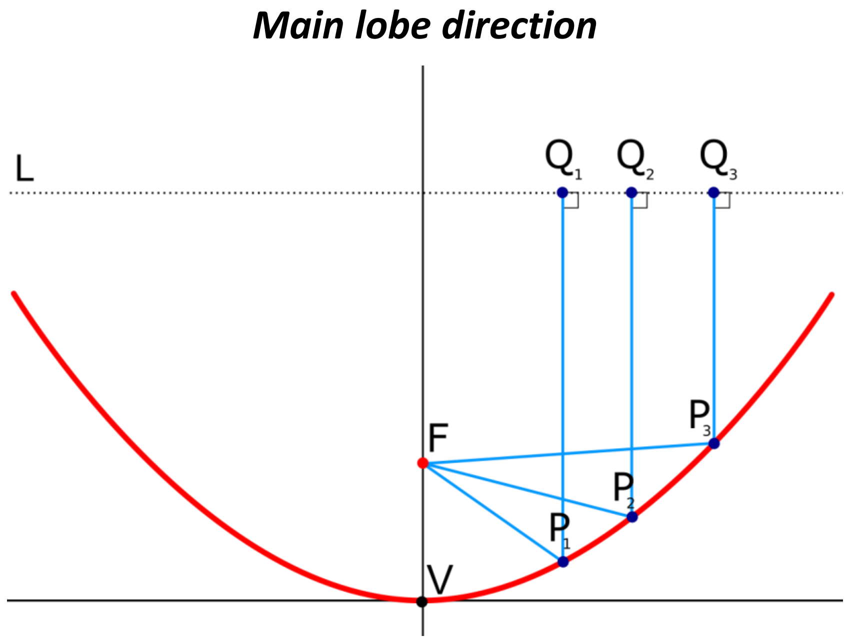
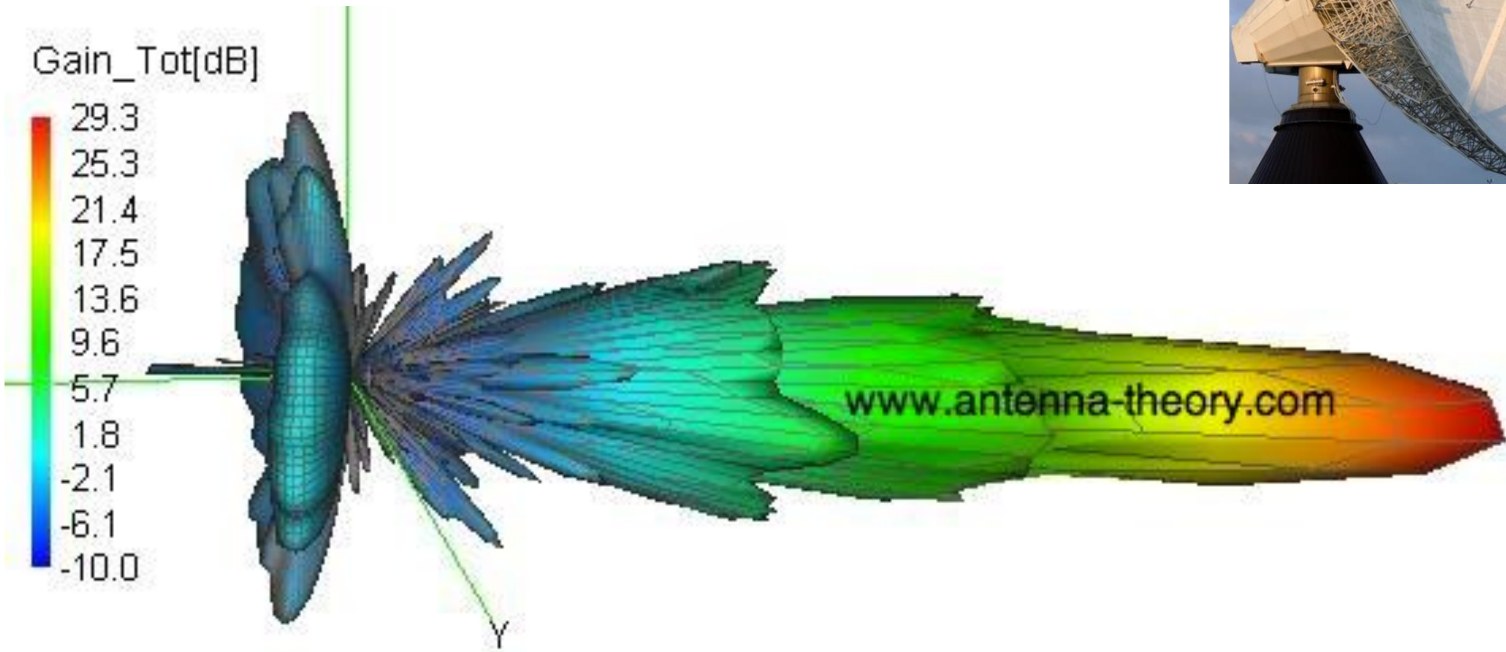
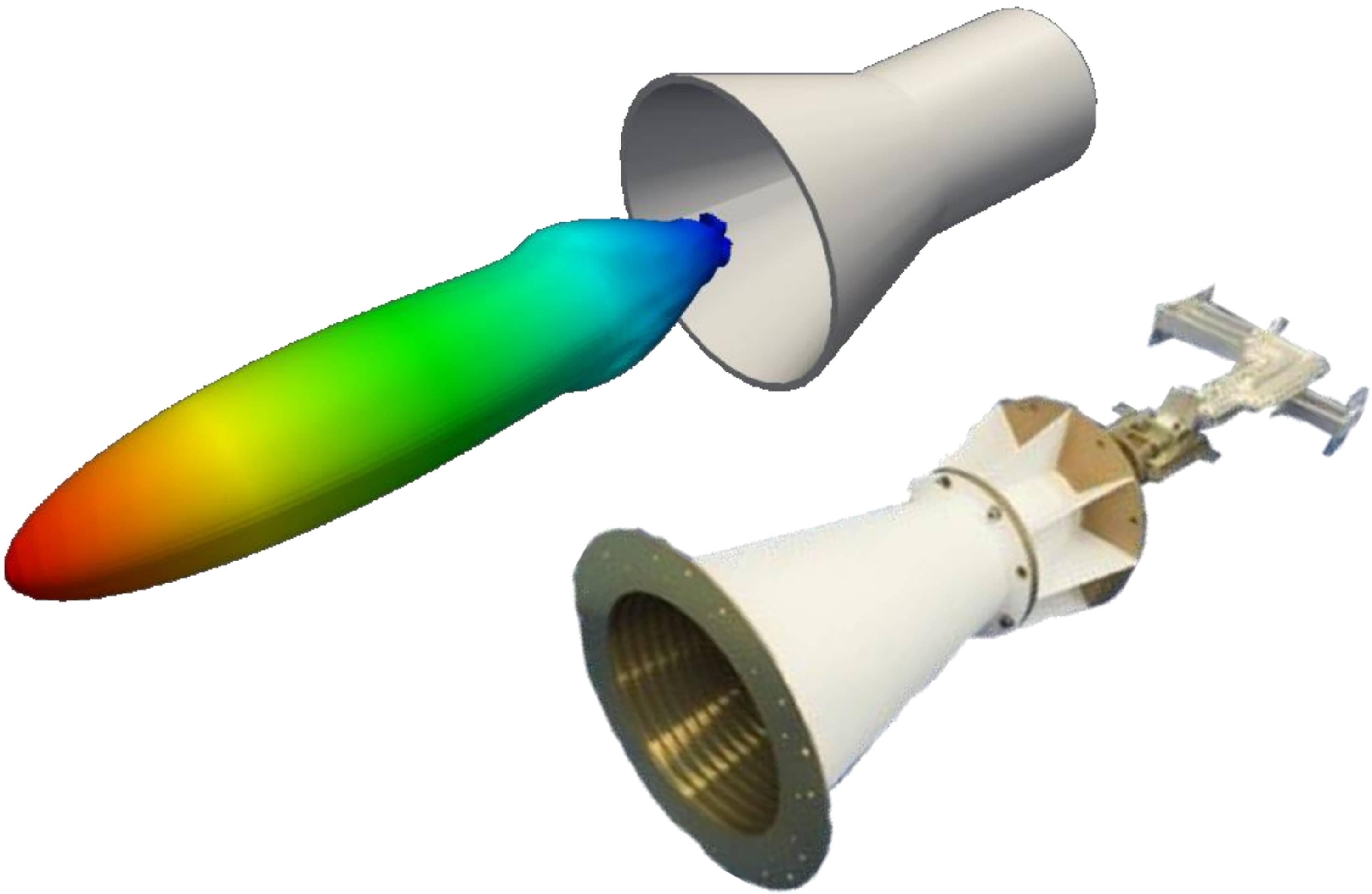


$$A_e = 0.5 \div 0.7A \quad \leftrightarrow \quad G = 6 \div 9\frac{A}{\lambda^2}$$

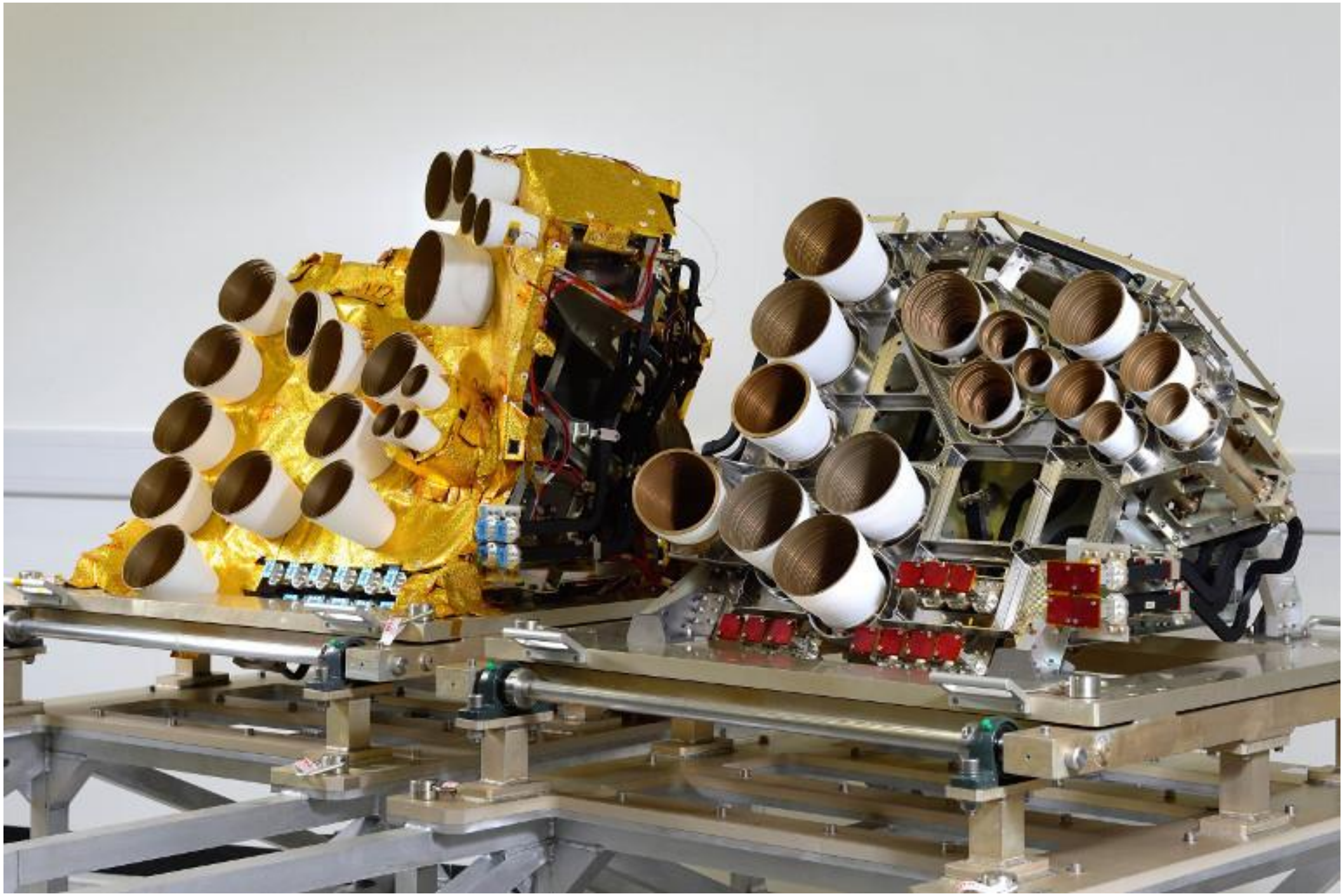
Example: Parabolic Antenna



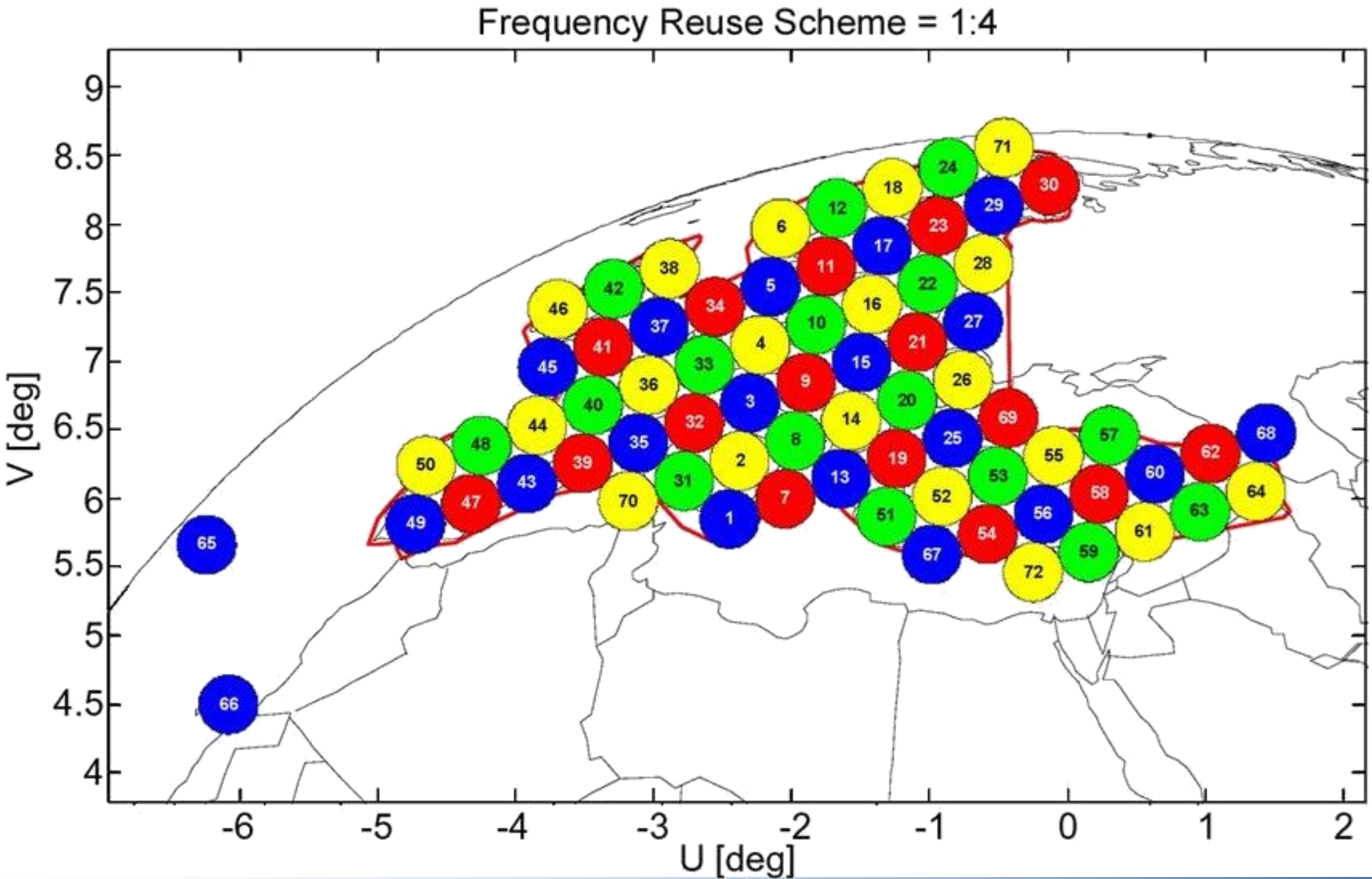
Horn Antenna



Multibeam Horn Antenna…



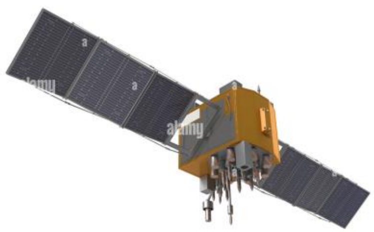
…and its footprint



Link Budget 1 – Received power

$$P_R = P_T \frac{G_T G_R}{(4\pi h/\lambda)^2}$$

$$P_R\big|_{dBW} = P_T\big|_{dBW} + G_T\big|_{dB} - L\big|_{dB} + G_R\big|_{dB} = P_T\big|_{dBW} + G_T\big|_{dB} - 20\log\left(\frac{4\pi h}{\lambda}\right) + G_R\big|_{dB}$$



GPS satellite

- Satellite RF power: P_T=25.6 W=14 dBW
- TX Antenna gain (max): G_T= 12 dB (dBi)
- *EIRP* = $P_{T\ (dB)}$ + $G_{T\ (dB)}$ =26 dBW (about 500 W equivalent)
- Satellite altitude: *r*=20,200 km
- Free-Space Loss @ f_0=1575 MHz: $L=(4\pi h)^2/\lambda^2$ $= (4\pi h f_c)^2 / c^2$= 182 dB
- RX antenna gain (smartphone): G_R =-1 dBi
- Received Power at RX antenna output: $C=EIRP-L+G_R$=-157 dBW=0.2 fW (2. 10^{-4} pW)=0.1 μV in 50 Ω

Link Budget 2 - Noise Computation

- P_R is also called C (carrier power)
- k_B= Boltzmann's constant
- T_n=RX Noise Temperature
- T_b, R_b = bit time, bit rate

$$\frac{E_b}{N_0} = \frac{C\,T_b}{k_B T_n} = \frac{C}{R_b k_B T_n}$$

$$C\,\Big|_{dBW} = EIRP_{dBW} - 20\log\left(\frac{4\pi h}{\lambda}\right) + G_R\Big|_{dB}$$

$$\frac{C}{N_0}\Bigg|_{dBW} = EIRP_{dBW} - 20\log\left(\frac{4\pi h}{\lambda}\right) + G_R\Big|_{dB} - 10\log(k_B T_n)$$

$$\frac{E_b}{N_0}\Bigg|_{dB} = EIRP_{dBW} - 20\log\left(\frac{4\pi h}{\lambda}\right) + \frac{G_R}{T_n}\Bigg|_{dB/K} - 10\log(k_B R_b)$$

TX — Propagation — RX — Bit-rate

Refining the Link Budget

- Propagation Impairments
  - Adds-up on top of free-space loss and is variable from day to day and within the day
  - Diminish the received RF power
- Transmitter/Receiver Losses
  - Coming form connectors, waveguides, between the HPA/LNA and the antenna
  - Diminishes the nominal TX/RX useful power
- Noise
  - A relevant component coming form the antenna looking at the sky has to be taken into account
  - The noise figure of the receiver also comes into play
  - More than just thermal noise…

Noise Figure & Noise Temperature

$$N_{DUT} = Gk_B T_{DUT} = GN_{in}(F-1)$$

where the internal noise is referred to the device *input.* Conventionally, the input-referred internal noise is expressed via the reference temperature $T_{ref=}$290 K:

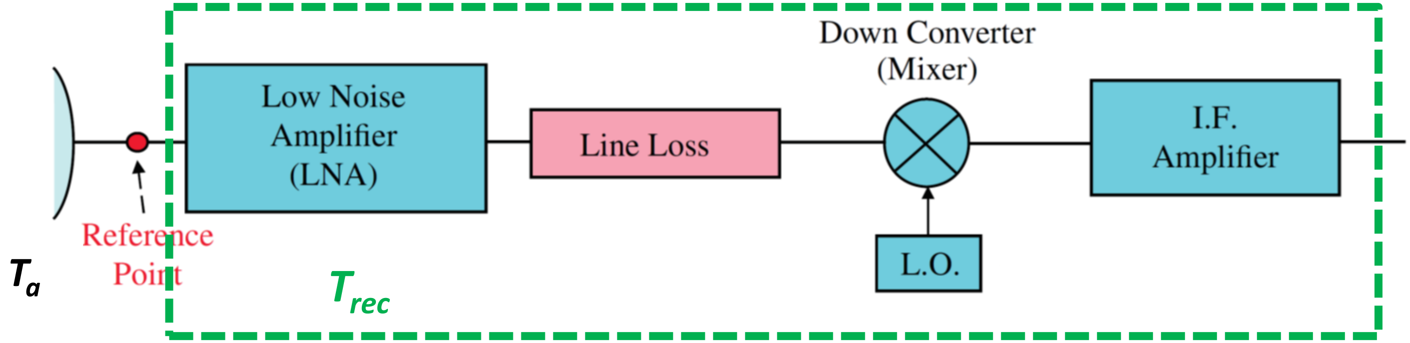
$$N_{in} = k_B T_{ref} \quad \Rightarrow \quad N_{DUT} = Gk_B T_{ref}(F-1) \quad \Rightarrow \quad T_{DUT} = T_{ref}(F-1)$$

and the relation between the Noise Figure *F* and the Equivalent Noise Temperature T_{DUT} is

For cascaded devices,

$$F_{tot} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \ldots + \frac{F_N - 1}{G_1 G_2 \ldots G_{N-1}} \quad \Rightarrow \quad T_{tot} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \ldots + \frac{T_N}{G_1 G_2 \ldots G_{N-1}}$$

System Noise Components



Receiver Noise

Element	Cumulative NF [dB] @ Output
OMT	0.41
LNA	2.71
AMP	2.73
IR Filter	2.74
Mixer	2.80
IF Filter	2.82
IF Amp 1	2.87
IF Amp 2	2.88
Total (NF)	2.88

F_{rec}=2.88 dB=1.94

therefore T_{rec} =(F-1) T_{ref} =272.6 K

The *antenna* is also generating noise – so what is missing here is the ANTENNA NOISE T_a to find the overall system noise temperature T_{tot} (aka T_{sys})

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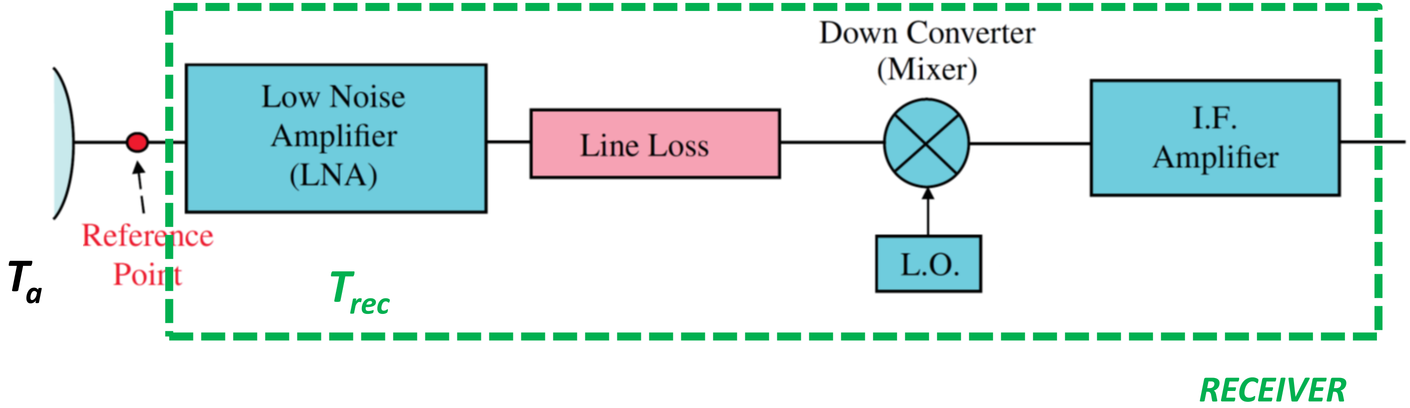
Including the Antenna Noise

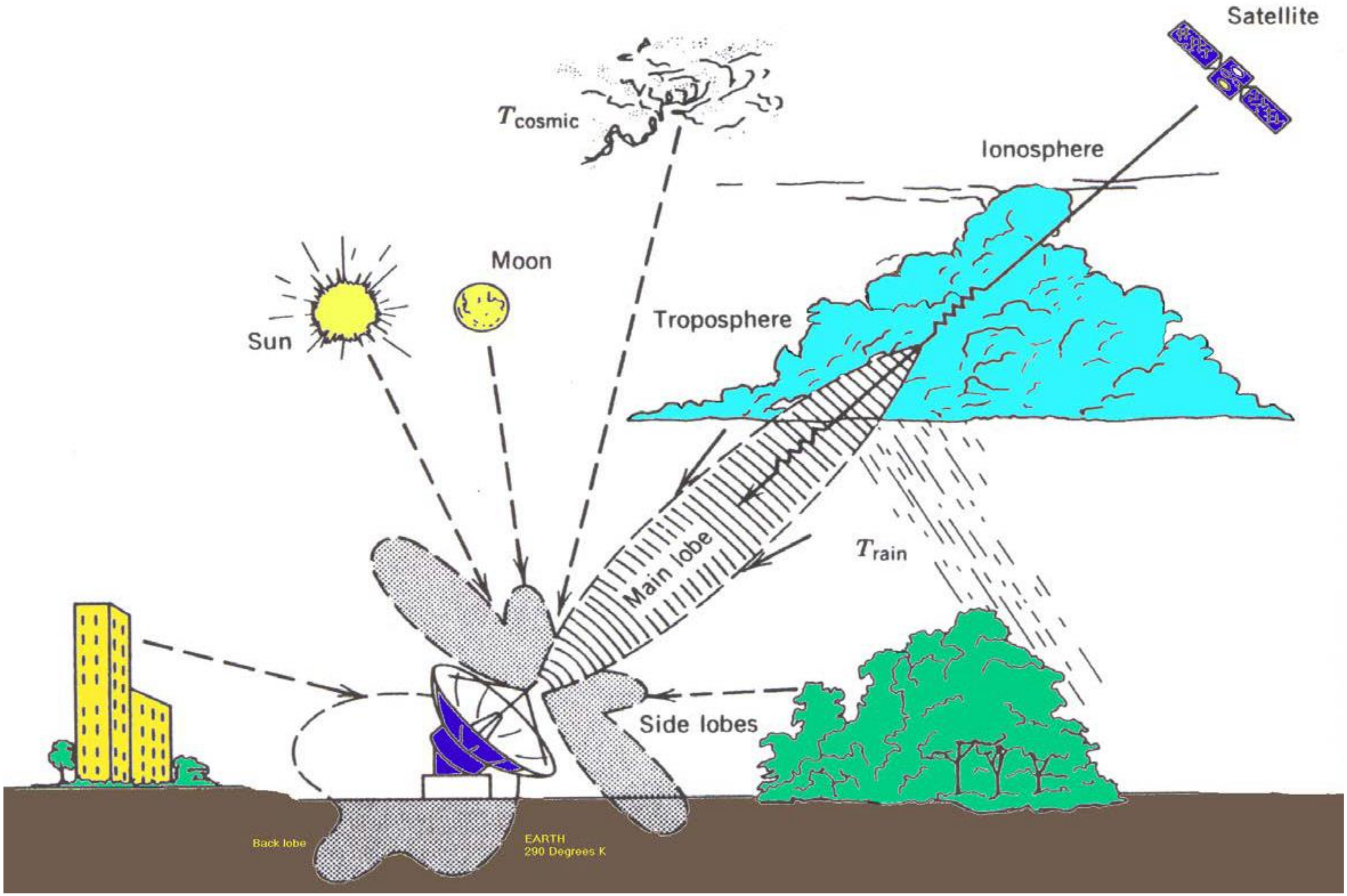


- The antenna is directly connected to the receiver input (LNA)
- The noise temperature of the receiver is referred to the same Reference Point
- Therefore, the two temperatures just add up to give the *total system noise temperature*

$$T_{tot} = T_a + T_{rec}$$

- What is left to do is, finding the ***noise temperature of the antenna***

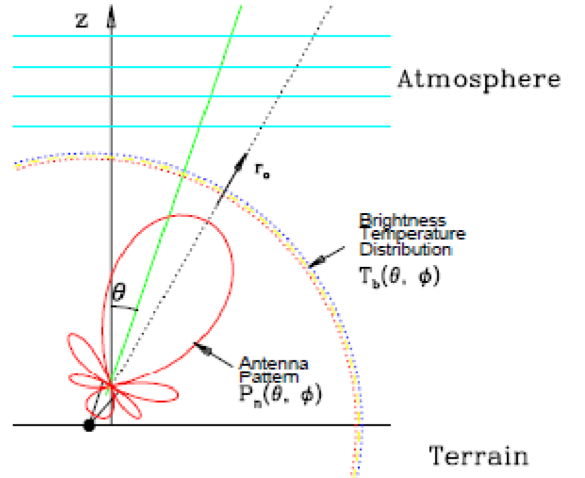
Earth Antenna Picking up Noise



Antenna Noise Temperature

- **ON EARTH** It is caused by the radiation of the various celestial bodies within the antenna beamwidth, causing an equivalent point-by-point noise temperature T_a:

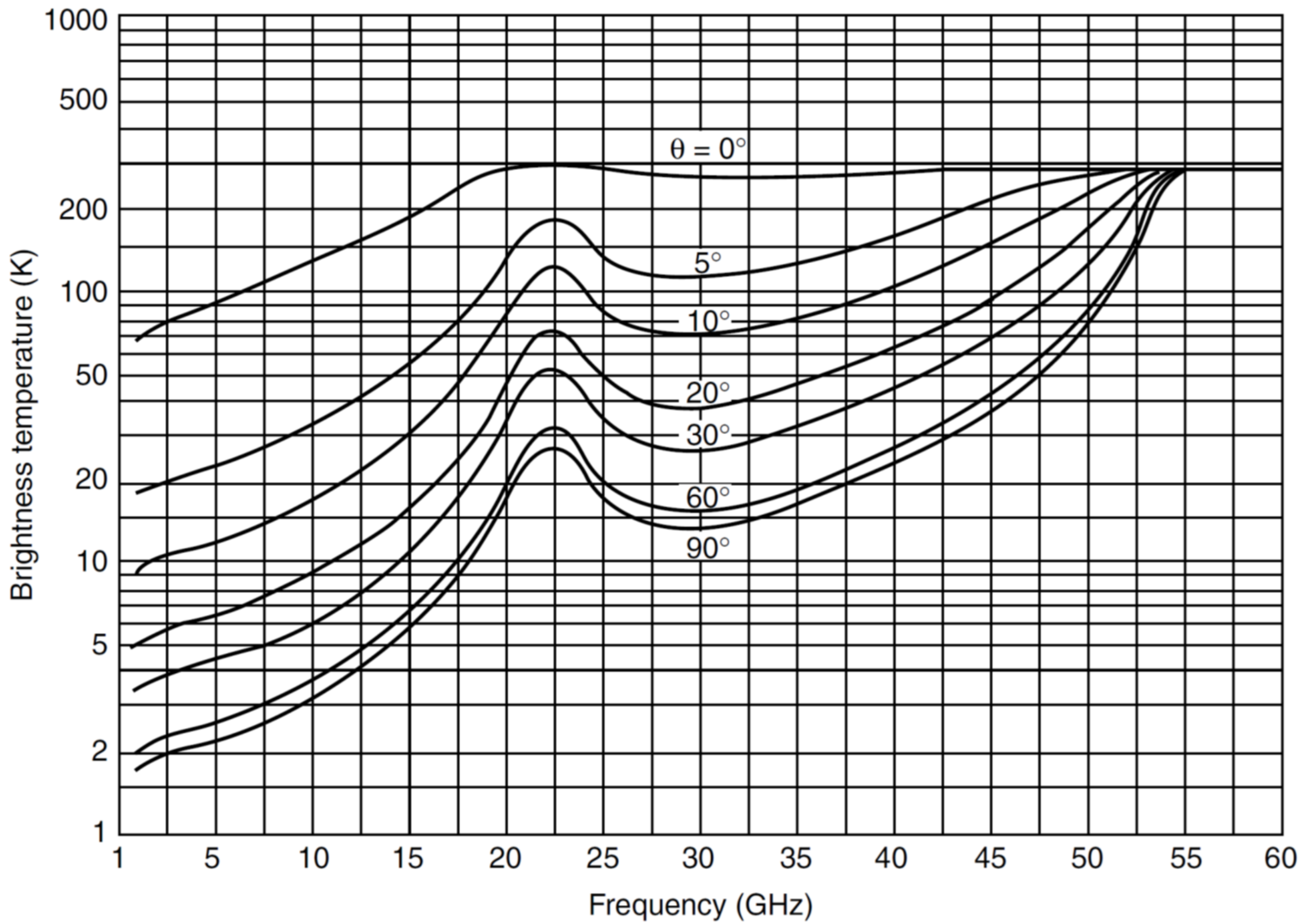
$$T_a = \frac{1}{4\pi} \iint T_b(\theta, \varphi) G(\theta, \varphi) \sin(\theta) d\theta d\varphi$$



- Since the celestial bodies are relatively cold, the antenna temperature is (relatively) low wrt T_{ref}
- **AT THE SATELLITE**, the contribution comes mainly from the Earth and depends on the areas within the beamwidth (coverage) of the antenna
- Ground (warmer) radiates more than Oceans (cooler)
- Maps of radiating noise are available for accurate computations
- In general, a safe value of T_a=290 K can be used.

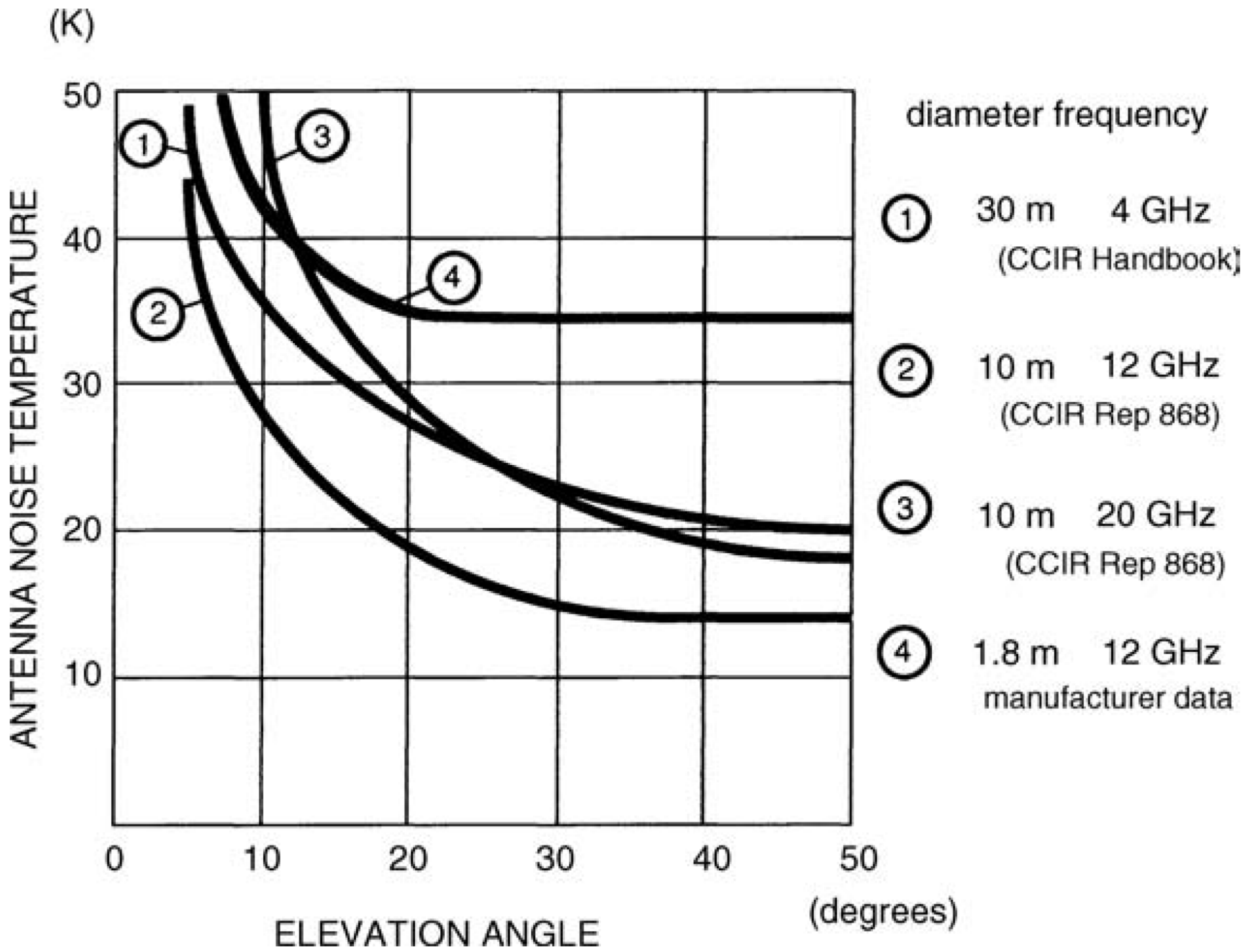
Antenna Noise on the Ground 1/2

Radiation of the sky and from the ground both contribute, the latter coming from secondary lobes of the radiation pattern. For low frequencies, radiation from the sky is low

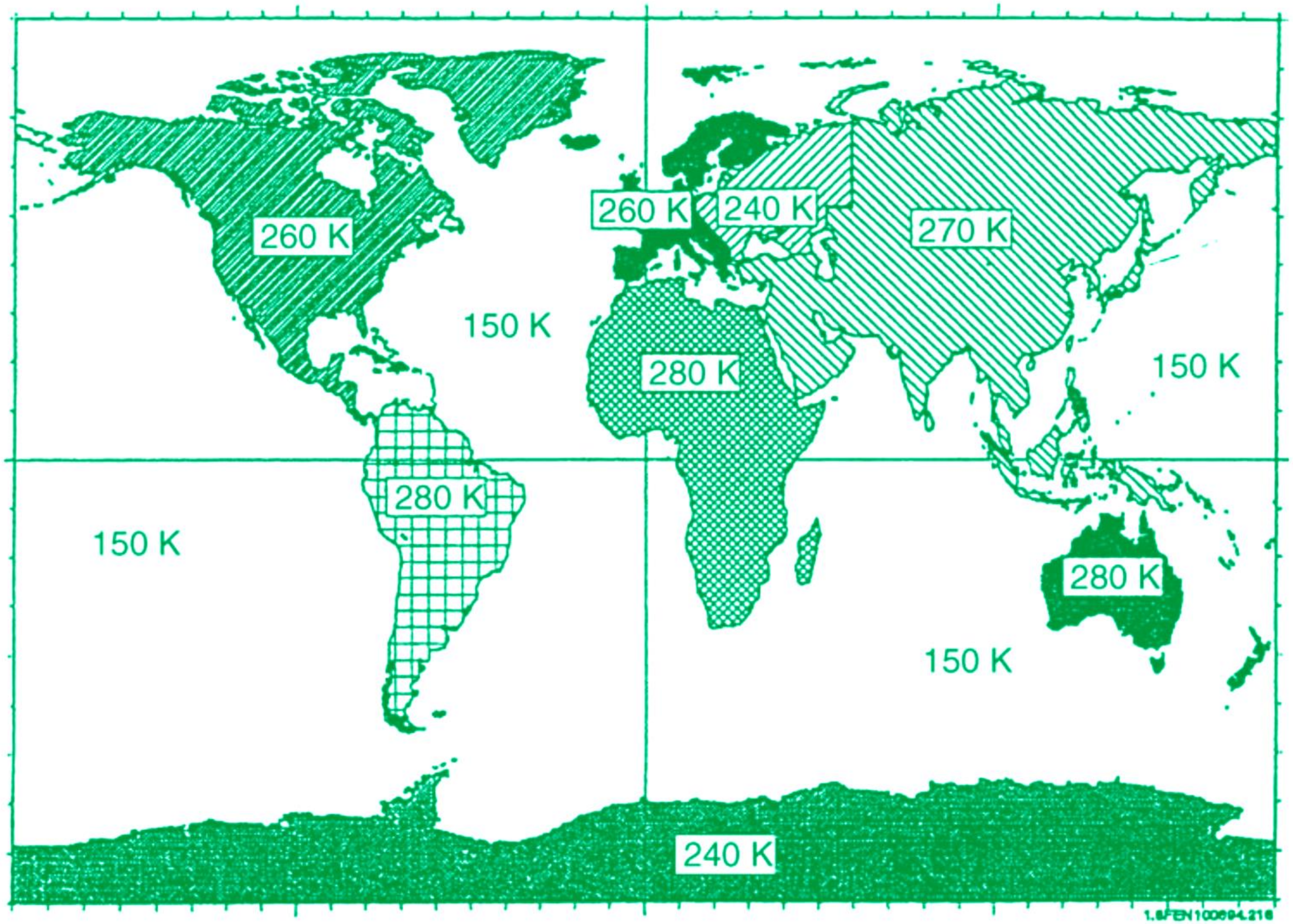


Antenna Noise on the Ground 2/2

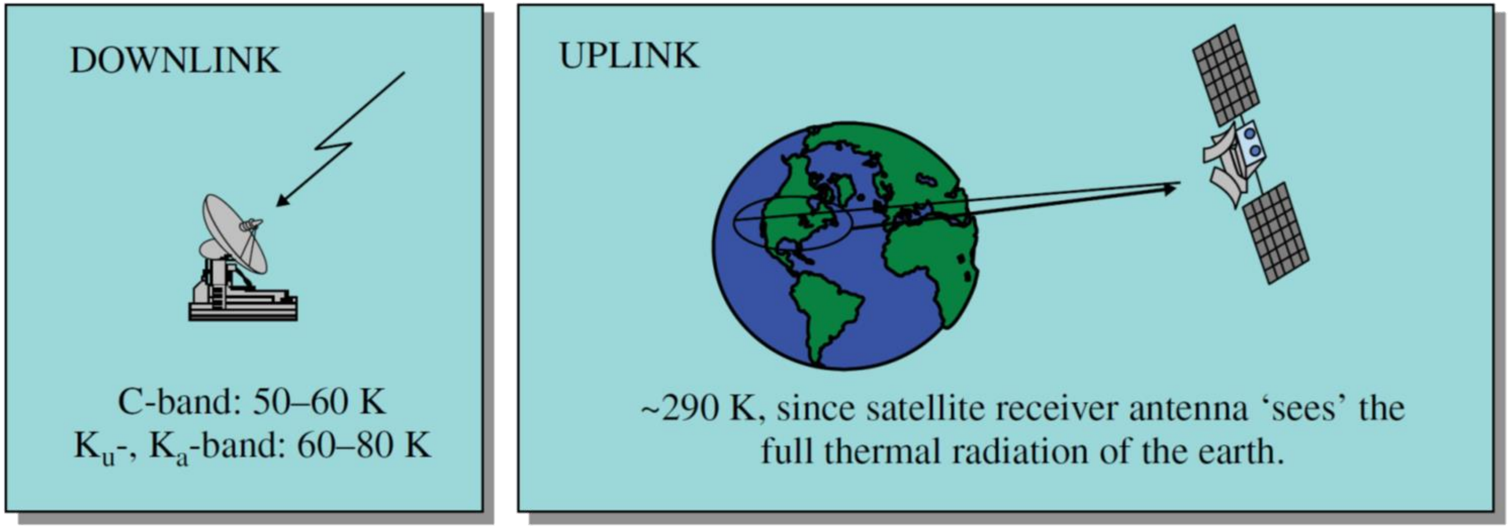
- A safe value of 50 K can be used.
- There may also be a noise increase during heavy rain events due to the emission of the rain drops at their own temperature of 270 K.



SAT Antenna Earth-Induced noise @ Ku band (ESA/Eutelsat)



Antenna Temperature Summary



(a)

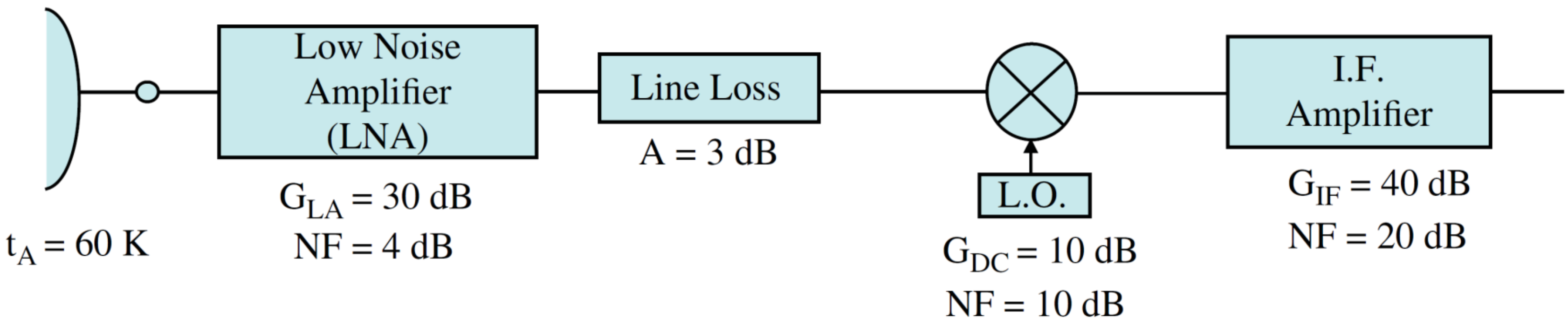
TYPICAL ANTENNA TEMPERATURE VALUES (NO RAIN)

Rain Fade Level (dB)	1	3	10	20	30
Noise Tempeature (°K)	56	135	243	267	270

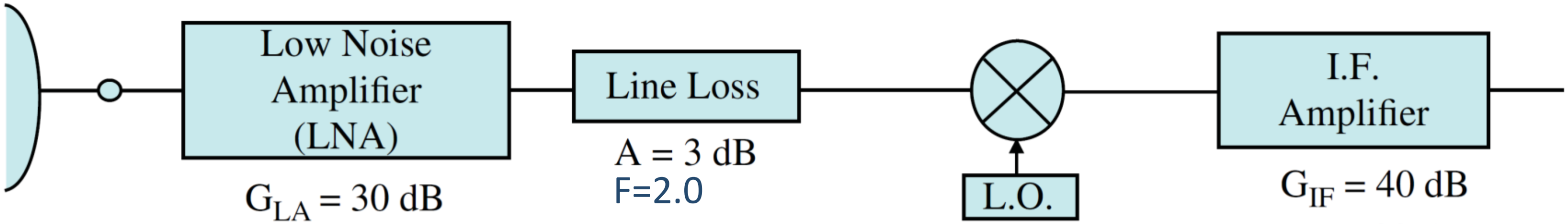
(b)

ADDITIONAL RADIO NOISE CAUSED BY RAIN

Sample Noise Computation



Sample Noise Computation



$t_A = 60$ K

$G_{LA} = 30$ dB
NF = 4 dB =2.51
T_{LNA}=(2.51-1)290=439 K

A = 3 dB
F=2.0
T_L=290 K

$G_{DC} = 10$ dB
NF = 10 dB=10
T_{MIX}=2610 K

$G_{IF} = 40$ dB
NF = 20 dB=100
T_{IFA}=28710 K

$$T_{rec} = T_{LA} + \frac{T_L}{G_{LA}} + \frac{T_{MIX}}{G_{LNA} \cdot 1/A} + \frac{T_{IFA}}{G_{LA} \cdot 1/A \cdot G_{DC}}$$ =438+0.29+ 5.22+5.74=449 K

T_{sys}=60+449=509 K , F_{sys}=4.4 dB

(Further) Considerations on the link budget

$$P_R = P_T \frac{G_T G_R}{(4\pi h / \lambda)^2}$$

- The received power appears to *decrease for decreasing wavelength*. BUT, let us assume that the ***size*** (i.e., the physical area) of the antennas on board the satellite and at the ground are constrained (as is often the case), and re-formulate the equation introducing the antenna equivalent areas $A=\lambda^2 G/(4\pi)$

$$P_R = P_T \frac{A_T A_R}{(\lambda h)^2}$$

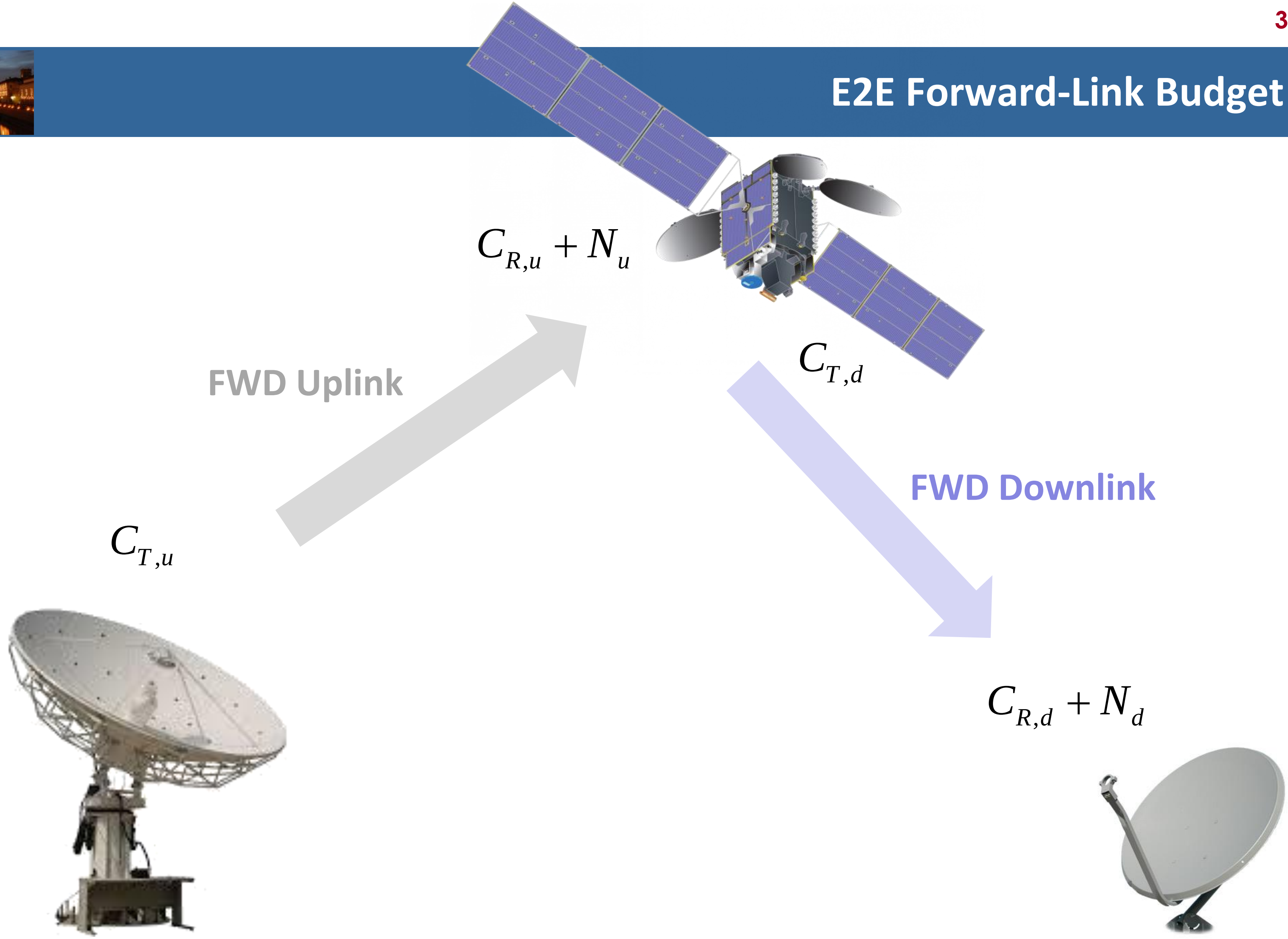
- It is clearly seen that the received power (hence the link budget) *increases decreasing the wavelength* – this is because, for the same physical size, the gain of the antennas increases for a reduced wavelength
- The noise is on the contrary largely independent of the wavelength.... This is yet another reason for the run towards higher frequencies

To the link budget again

$$\left.\frac{E_b}{N_0}\right|_{dB} = EIRP_{dBW} - 20\log\left(\frac{4\pi h}{\lambda}\right) - L_{prop} + \left.\frac{G_R}{T_{sys}}\right|_{dB/K} - 10\log(k_B R_b) - M$$

- Sample computation, EUTELSAT KONNECT, (16 degrees E), Ka-band data connectivity
  - Downlink: EIRP 52 dBW, 20 GHz, *G*/*T*=19 dB/K
  - Uplink: G_T=44 dBi, 30 GHz, *G*/*T*=? (assume same C/N_0 as in the uplink)
  - Link Budget Spreadsheet
- Sample computation, GPS satellite with antenna and receiver noise

E2E Forward-Link Budget



E2E Forward-Link Budget

Transponder Gain G

$$SNR_{up} = \frac{C_{R,u}}{N_u} = \frac{C_{T,u}/L_u}{N_u}$$

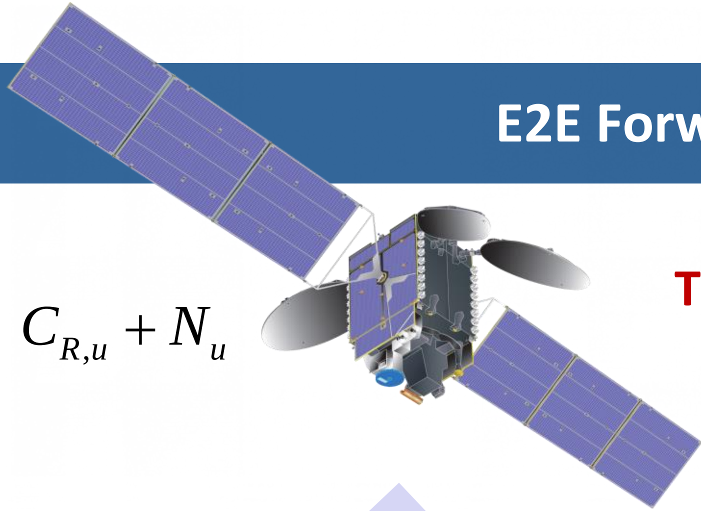
$$N_u = kT_{sys,u}B$$

$C_{T,u}$

$$SNR_{down} = \frac{C_{R,d}}{N_d} = \frac{C_{T,d}/L_d}{N_d}$$

$$N_d = kT_{sys,d}B$$

E2E Forward-Link Budget



$$C_{R,u} + N_u$$

Transponder Gain *G*

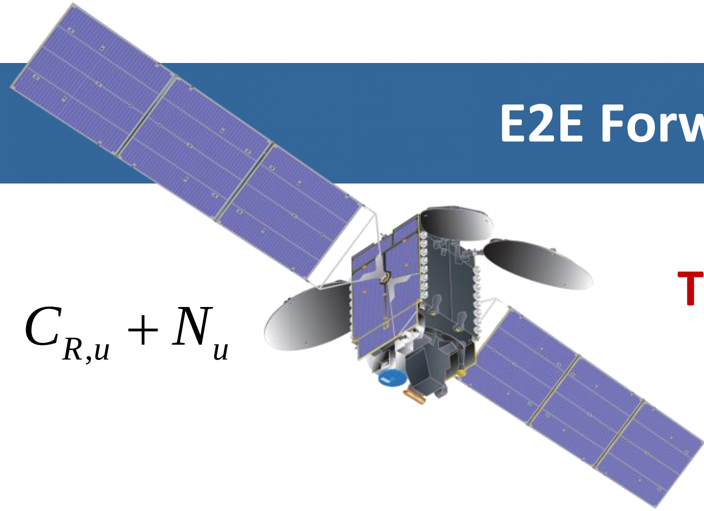
$$C_{T,d} = GC_{R,u} = GC_{T,u} / L_u$$

$$C_{T,u}$$

$$C_{R,e2e} = \frac{C_{T,u}}{L_d} = \frac{C_{T,u}G}{L_u L_d}$$

$$N_{R,e2e} = \frac{GN_u}{L_d} + N_d$$

E2E Forward-Link Budget



$$C_{R,u} + N_u$$

Transponder Gain *G*

$$\left(\frac{N}{C}\right)_{e2e} = \frac{N_{R,e2e}}{C_{R,e2e}} = \frac{\dfrac{GN_u}{L_d} + N_d}{\dfrac{C_{T,u}G}{L_u L_d}} = \frac{N_u}{C_{T,u}/L_u} + \frac{N_d}{\dfrac{C_{T,u}G}{L_u L_d}} = \frac{N_u}{C_{T,u}/L_u} + \frac{N_d}{C_{T,d}/L_d} = \left(\frac{N}{C}\right)_u + \left(\frac{N}{C}\right)_d$$

$$\frac{1}{(C/N)_{e2e}} = \frac{1}{(C/N)_u} + \frac{1}{(C/N)_d}$$

E2E Link Budget - Considerations

- In a direct-to-the-user network, the *Forward Link* (from the network to the end-user) is *user-limited*, meaning that C/N for the user downlink is much smaller than the C/N of the feeder uplink (featuring the high-gain ground-station antenna). In this case, the large C/N value in the "harmonic mean" formula can be neglected and $(C/N)_{e2e} \approx (C/N)_d$.

- Same considerations apply to the *Return Link* (from the end-user to the network): it is usually (uplink) *user-limited* so that $(C/N)_{e2e} \approx (C/N)_u$

- The remarks above are not true for a *trunk communications point-to-point scenario* where the two ends are two ground stations with similar-quality antennas and receivers.