DESIGN WORKSHOP: Regional Multibeam Satellite System

Pierre GRUYER, Simon PAILLARD, Max SUISSE DE SAINTE CLAIRE
pierre.gruyer@enst-bretagne.fr, simon.paillard@supaero.fr, suisse@supaero.fr

15 novembre 2005

1 Required $\left(\frac{C}{N}\right)_T$

1.1 Number of carriers

There is one carrier per one-way link between station and zone. Given there are 3 zones, we get :

$$N_{carriers} = \underbrace{3}_{zones} \times \underbrace{8}_{stations\ per\ zone} \times \underbrace{3}_{1\ carrier\ per\ one-way\ link} = 72$$

1.2 Carrier caracteristics

There are 24 transponders available for 72 carriers :

$$\Rightarrow 3\ carriers\ /\ transponder$$

Given 10% of margin in each channel, 3.6 Mhz are reserved as guard band per channel :

$$\Rightarrow 10.8 Mhz\ /\ carrier$$

1.3 Traffic load

We assume the 5 million user are evenly reparted on the 24 earth stations.

$$A_{Earth\ Station} = \underbrace{\frac{3}{24 \cdot 60}}_{mean\ call\ per\ day} \cdot \underbrace{\frac{5 \cdot 10^6}{72}}_{users\ per\ carrier} = 145E$$

1.4 Required multiplex capacity

A rule of thumb gives a required capacity $C = A + k \cdot A^{0.5}$ for a blocking probability of $p = 10^{-k}$. Since the blocking probability (here $p = 1\%$ thus $k = 2$) is relative to a given multiplexe pool of voice channels :

$$\Rightarrow C_{required} = 170 \text{ required voice channels per carrier}$$

According to the standard multiplex capacities, we will use what implies :

$$\begin{cases} C_{per\ carrier} = 192 \\ f_{min} = 12kHz \\ f_{max} = 804kHz \end{cases}$$

1.5 Total network capacity

$$C_{total} = C_{per\ carrier} \cdot N_{carriers} = 13824 \ voice\ channels = 6912 \ circuits$$

1.6 Required $\left(\frac{C}{N_0}\right)_T$

$$\left(\frac{C}{N_0}\right)_T = \frac{\frac{S}{N}}{\left(\frac{\Delta F_r}{f_m}\right)^2 \cdot \left(\frac{1}{b}\right) \cdot p \cdot w}$$

Under clear sky conditions, $S_{test\ tone}$=1 mW and the 10000 $pWOp$ noise is composed of

- 7500 $pWOp$ for all sources of noise but external interference
- 2500 $pWOp$ for external interferences

$$\Rightarrow \frac{S}{N} = \frac{1\ mW}{7500\ pW} \ ; \ \left(\frac{S}{N}\right)_{dB} = 51.3\ dB$$

Given $\Delta F_r = \frac{\frac{B}{2} - f_m}{g \cdot L}$ with $g = \sqrt{10}$ and $L = 10^{\frac{-1+4 \cdot log(192)}{20}}$, $p = 4\ dB$, $w = 2.5\ dB$, $b = 3100\ Hz$, $B = 10.8\ Mhz$:

$$\left(\frac{C}{N_0}\right)_T (dB) = 51.3 + 3 + 34.9 - 4 - 2.5 = 82.7\ dBHz$$

1.7 Required $\left(\frac{C}{N}\right)_T$

$$\left(\frac{C}{N}\right)_{T\ required} = \left(\frac{C}{N_0}\right)_T \cdot \frac{1}{B}$$

$$\left(\frac{C}{N}\right)_{T\ required}(dB) = 82.7 - 10 \cdot log(10.8 \cdot 10^6) = 12.3\ dB$$

This value is higher than the demodulator threshold which is 7 dB. We should compare the values in order to know if the signal will be properly demodulated. 5.3 dB margin is quite few in clear sky conditions.

2 $\left(\frac{C}{N}\right)_T$ as a fonction of the input back-off (IBO)

2.1 Uplink carrier over noise ratio

$$\left(\frac{C}{N}\right)_U = \frac{P_i^3}{N_U} = \frac{(P_i^1)_{sat}}{N_U} \cdot IBO = A_U \cdot IBO \Rightarrow A_U = \left(\frac{C}{N}\right)_{U_{saturation}}$$

To determine a numerical value, we use :

$$\left(\frac{C}{N}\right)_{U_{saturation}} = \frac{C_{U_{saturation}}}{k \cdot T_U \cdot B_N}$$

- k : boltzman's constant
- T_U : uplink system noise temperature
- B_N : bandwidth of one carrier of the earth station receiver

2.1.1 Carrier level at saturation

At the input of the receiver, $C_{U_{saturation}} = \frac{P^1_{O_{sat}}}{G_{SL}}$ where $G_{SL_{dB}} = \sum_i G_i - \sum_j L_j$ is the gain from the input of the redundant R_X to the output of the TWTA. The calculation is done in the worst case, in order to avoid saturation in all other cases. Thus, we choose the more attenuated path.

$$G_{SL}\ (dB) = 20 + 20 - 10 + 10 - 0.1 - 3.1 - 1.1 - 0.1 - 0.2 - 5 - 25 - 55 = 110.4dB$$

Given that $P^1_{O_{sat}} = 50\ W$, we get :

$$C_{U_{saturation}} = \frac{50}{10^{+11.04}} = -93.4dBW$$

2.1.2 Uplink system noise temperature

The uplink system noise temperature is given by :

$$T_U = \frac{T_{Ant}}{L_{FRx}} + T_F\left(\frac{1}{L_{FRx}}\right) + T_{Rx}$$

Considering the satellite at $T_0 = 290\ K$, any passive attenuator generates a noise figure F equal to its loss factor L. By using the Friss formula, we get $F_{Rx} = 2.86$ and then :

$$T_{Rx} = (F - 1)T_0 = 539.9K$$

The noise of earth seen by the antenna is : $T_{Ant} \approx 290\ K \approx T_F$.
Thus :

$$\begin{cases} T_U = 829.9\ K \\ A_U = 3689 \\ A_U(dB) = 35.7dB \end{cases}$$

2.2 Intermodulation noise

$$\left(\frac{C}{N}\right)_{IM} = \frac{{}^3P_{out}}{P_{IM}} = \frac{OBO \cdot\ {}^1P_{O\ sat}}{IM \cdot\ {}^1P_{O\ sat}} = \frac{OBO}{IM}$$

2.3 Downlink carrier over noise ratio

$$\begin{aligned} \left(\frac{C}{N}\right)_D &= {}^3P_O \cdot G_{sat} \cdot \frac{1}{L_D} \cdot \left(\frac{G}{T}\right)_{ES} \cdot \frac{1}{k \cdot B_N} && (1) \\ &= {}^1P_{O\ sat} \cdot G_{sat} \cdot \frac{1}{L_D} \cdot OBO \cdot \left(\frac{G}{T}\right)_{ES} \cdot \frac{1}{k \cdot B_N} && (2) \\ &= A_D \cdot OBO \cdot \left(\frac{G}{T}\right)_{ES} && (3) \end{aligned}$$

Thus,

$$A_D = \frac{{}^1P_{O\ sat} \cdot G_{sat}}{kL_DB_N}$$

2.4 Satellite transmit antenna reflector

Considering depointing values in yaw, pitch and roll axis, as well as in latitude, longitude and endly depointing of the boresight with respect to the reference axes of the satellite, the following table gives values in degrees ($^\circ$) for the different depointing components :

Zone	*A*	*B*	*C*	*Global*
$\Delta\theta_{SK_x}$ at node	4.0410^{-3}	4.7410^{-3}	3.2310^{-3}	3.9610^{-3}
$\Delta\theta_{SK_y}$ at node	1.1510^{-2}	1.2710^{-2}	1.3010^{-2}	1.2710^{-2}
$\Delta\theta_{SK_x}$ at vertex	8.8810^{-3}	9.1910^{-3}	8.3610^{-3}	8.9210^{-3}
$\Delta\theta_{SK_y}$ at vertex	7.7210^{-3}	9.4110^{-3}	1.0110^{-2}	9.5010^{-3}
$\Delta\theta_{AC_x}$	5.0010^{-2}	5.0710^{-2}	5.0010^{-2}	5.0110^{-2}
$\Delta\theta_{AC_y}$	4.2610^{-2}	3.9810^{-2}	3.5110^{-2}	3.8310^{-2}
$\Delta\theta_x$ at node	5.4010^{-2}	5.5410^{-2}	5.3210^{-2}	5.4110^{-2}
$\Delta\theta_y$ at node	5.4110^{-2}	5.2410^{-2}	4.8010^{-2}	5.1010^{-2}
$\Delta\theta_x$ at vertex	5.8910^{-2}	5.9910^{-2}	5.8410^{-2}	5.9010^{-2}
$\Delta\theta_y$ at vertex	5.0310^{-2}	4.9210^{-2}	4.5210^{-2}	4.7810^{-2}
$\Delta\theta_m$ at node	0.076	0.076	0.072	0.074
$\Delta\theta_m$ at vertex	0.077	0.077	0.074	0.076
$\Delta\theta_m$	0.077	0.077	0.074	0.076
$\Delta\theta$	0.102	0.102	0.099	0.101
θ_{total}	0.95	0.95	0.95	2.98

As we know θ_{3dB}, we will determine the diameter of the transmit antenna reflector, in order to fulfil requirements of all zones and every frequencies. As :

$$\theta_{3dB} = \frac{70 \cdot c}{D \cdot f} \Leftrightarrow D = \frac{70 \cdot c}{f \cdot \theta_{3dB}}$$

Since for a given diameter D in the downlink, $\theta_{3dB_{min}}$ corresponds to f_{max} so f_{max} is used in the calculation. Thus, the coverage of lower frequencies signals will be better.

$$D_{SL,Tx} = 1.88\ m$$

2.5 Interference noise

The overall $\left(\frac{C}{N}\right)_I$ has a downlink and a uplink contribution.
We do the following assumptions :

- the free space loss for horizontally and verticaly polarised signals are identical
- the delta in the different receiving levels in the primary lobe is neglictable compared to the high relative gain of the primary lobe
- all earth stations emit at the same level.

Intermodulation noise are taken into account in an other part.

Two cases have to be studied for a given frequency band in the downlink :

- the both polarizations come from the same zone, at a relative same level;
- the interfering polarization comes from a other zone than the wanted one, and is not received in the primary lobe of the antenna.

2.5.1 Uplink interferences

The uplink frequency plan is the downlink one with a fixed frequency shift. The satellite has an unique primary lobe on the receiving side.

- L_I and L_W represent space losses of respectively the interfering signal and the wanted signal.
- X_{sat} and X_{ES} are the cross-polarization isolation of respecively satellite antennas and earth stations antennas, in dB.
- G_I and G_W represent the antenna gain in the direction of intergering signal and wanted signal. We consider a $\left(\frac{G_W}{G_I}\right)_{dB}$ of $-1dB$ in the worst case.

The interference noise is due to the interfering signal and the impact of X_{sat} and X_{ES} on it. The effect of both X_{ES} and X_{sat} is directly proportionnal to the path loss and the antenna gain, because there are from the same earth station and the same original emitted signal.

Keeping the notation of the lesson,

$$\begin{cases} C_x = P_x \cdot \frac{G_w}{L_w} \\ I_x = C_y \cdot 10^{-\frac{X_{sat}}{10}} = P_y \cdot \frac{G_i}{L_i} \cdot 10^{-\frac{X_{sat}}{10}} \\ J_x = Q_x \cdot \frac{G_i}{L_i} = P_y \cdot 10^{-\frac{X_{es}}{10}} \cdot \frac{G_i}{L_i} \\ as\ P_x = P_y \\ \frac{C_x}{I_x+J_x} = \frac{G_w}{G_i} \cdot \frac{L_i}{L_w} \cdot \frac{1}{10^{-\frac{X_{sat}}{10}}+10^{-\frac{X_{es}}{10}}} \end{cases}$$

Finally :

$$\left(\frac{C}{N_I}\right)_U = \frac{1}{10^{\frac{-X_{sat}}{10}} + 10^{\frac{-X_{ES}}{10}}} \cdot \frac{L_I}{L_W} \cdot \frac{G_W}{G_I}$$

interferring station / wanted station	A	B	C
A	23.4	23.35	23.24
B	23.6	23.56	23.43
C	23.81	23.76	23.65

2.5.2 Downlink interferences

We follow the same reasoning as in uplink, except there are no terms taking into acount free space loss, since both wanted and interfering signals follow the same path between the satellite and the earth station.

$L_{interfering\ lobe}$ represents the absolute value of the difference of level between the first lobe and the lobe of the interfering signal. We assume the satellite emits at the same power level whatever is the earth station.

$$\left(\frac{C}{N_I}\right)_D = \frac{1}{10^{\frac{-X_{sat}}{10}} + 10^{\frac{-X_{ES}}{10}}} \cdot \frac{1}{L_{interfering\ lobe}}$$

$L_{interfering\ lobe}$ can have one out of two values :

– $(L_{interfering\ lobe})_{dB} = 0\ dB$ if the both polarizations come from the same zone in the worst case. Thus :

$$\left(\frac{C}{N_I}\right)_D = 24.6\ dB$$

– $(L_{interfering\ lobe})_{dB} \approx 17\ dB = (20dB - G_{max}) - (3dB - G_{max})$ if the interfering polarization is not received in the primary lobe of the wanted zone, which is itself on the edge of the coverage (at $G_{max} - 3\ dB$). Thus :

$$\left(\frac{C}{N_I}\right)_D = 41.6\ dB$$

2.5.3 Overall carrier over interference ratio

$$\left(\frac{C}{N_I}\right)^{-1} = \left(\frac{C}{N_I}\right)_U^{-1} + \left(\frac{C}{N_I}\right)_D^{-1}$$

We minimize interferences when there are no self beam interferences in downlink, while we maximize when there are self beam interferences in downlink.

The previous formula provides these $\left(\frac{C}{N_I}\right)_{dB}$ values :

interferring uplink station / wanted uplink station	A	B	C
A	23.3482	23.2941	23.1821
B	23.5358	23.4817	23.3698
C	23.7444	23.6904	23.5785

TAB. 1 – $\left(\frac{C}{N_I}\right)_{dB}$ minimizing downlink interferences

The worse $\left(\frac{C}{N_I}\right)$ without having self beam downlink interferences is $23,2dB$.

interferring uplink station / wanted uplink station	A	B	C
A	20.9503	20.9190	20.8538
B	21.0572	21.0266	20.9626
C	21.1739	21.1439	21.0813

TAB. 2 – $\left(\frac{C}{N_I}\right)_{dB}$ maximizing downlink interferences

The worse $\left(\frac{C}{N_I}\right)$ with self beam downlink interferences is $20,9dB$.

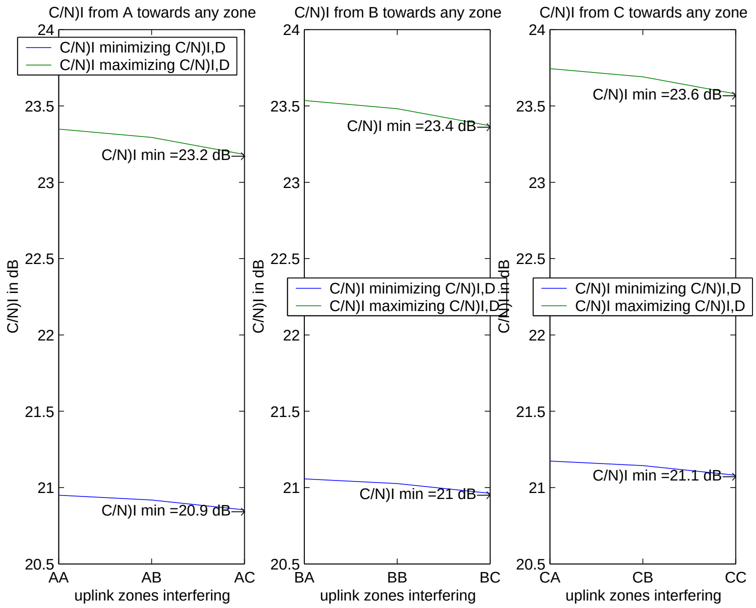


FIG. 1 – $\left(\frac{C}{N_I}\right)_{dB}$

2.6 Frequency plan & A_D

Several criteria have to be taken into account in the design of the frequency plan :

- Firstly, the about 2 dB difference between self-zone and between-zones $\left(\frac{C}{N_I}\right)$ leeds us to avoid at a given frequency the both polarization in the same zone.
- Moreover, since $\left(\frac{C}{N}\right)_D$ is a function growing with f, the higher is the frequency, the better is $\left(\frac{C}{N}\right)_D$. Thus, we will prefer high frequencies for further zones, like A zone. An other zone has to share the last third of frequency band with zone A : here we will prefer higher frequencies for zones with low elevation angle, i.e. zone B.
- In order to avoid interference with side lobes in the same zone, the both downlinks of a given zone will not use the same polarization.

All these constrains leed to the following downlink frequency plan :

Frequency band	11.2-11.36GHz	11.36-11.53 GHz	11.53-11.7 GHz
Horizontal polarization	B	C	A
Vertical polarization	C	A	B

For the considered clear sky frequency plan, we consider the worst case, i.d. the earth station is on the limit of downlink beam coverage ($G_T = G_{T_{max}} - 3dB$). We take into account the losses due to S4/3, OMUX, Output Filter (HF) and TWT to antenna feeder loss. So, we get the following A_D values :

Zone	A	B	C
A_D	11.33	11.63	12.1
$(A_D)_{dB}$	10.5	10.7	10.8

2.7 Minimum $\left(\frac{C}{N}\right)_T$

$$\left(\frac{C}{N}\right)_T^{-1} = \left(\frac{C}{N}\right)_U^{-1} + \left(\frac{C}{N}\right)_D^{-1} + \left(\frac{C}{N}\right)_I^{-1} + \left(\frac{C}{N}\right)_{IM}^{-1}$$

$\left(\frac{C}{N}\right)_U^{-1} + \left(\frac{C}{N}\right)_{IM}^{-1}$ is not depending on station to zone combination. As $\left(\frac{C}{N}\right)_D$ is minimized by a low A_D, we know that choose zone A as destination zone minimize $\left(\frac{C}{N}\right)_D$. As question 2.5 showed us that $\left(\frac{C}{N}\right)_I$ is lowest with station from zone A as emetor, the station to zone combination yielding the minimum $\left(\frac{C}{N}\right)_T$ for a given $\left(\frac{G}{T}\right)_{ES}$ is : station of zone A to zone A.

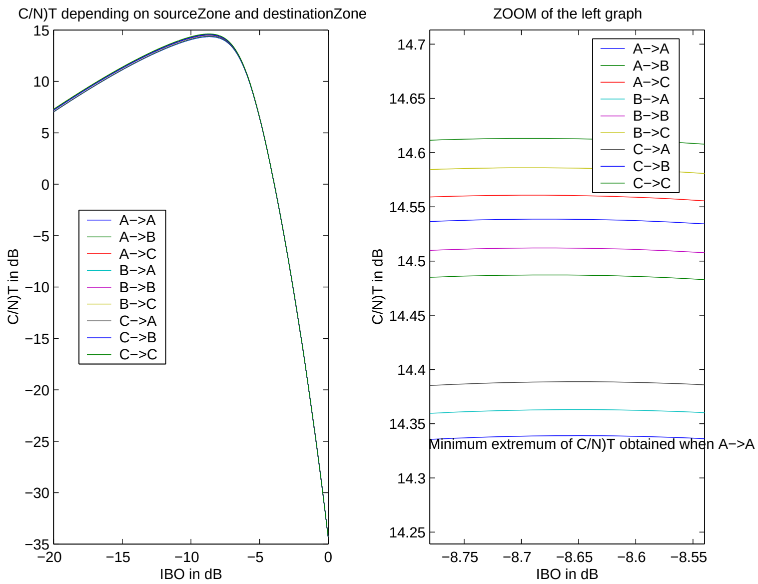


FIG. 2 – $\left(\frac{C}{N}\right)_{T_{dB}}$

2.8 $\left(\frac{C}{N}\right)_T$ as a fonction of the input back-off (IBO)

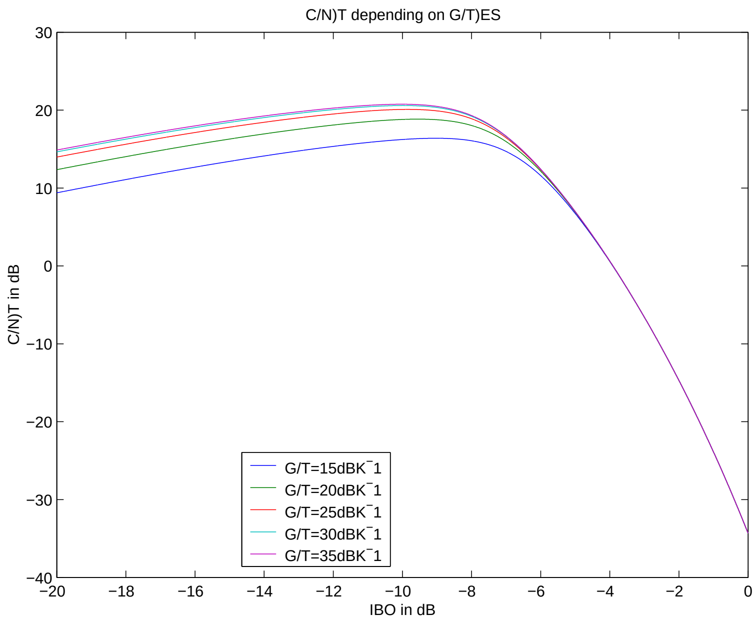


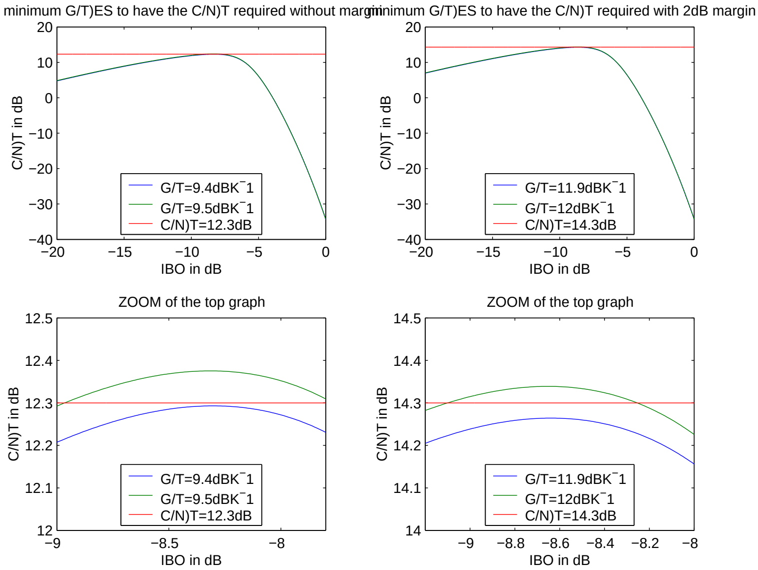
FIG. 3 – $\left(\frac{C}{N}\right)_{T_{dB}}$ fonction of IBO for several $\frac{G}{T}$

For low values of IBO, the curve grows up because IBO is decreasing what implies, so $\left(\frac{C}{N}\right)_U$ is increasing. And when $IBO > -10$, the curve goes down because $\left(\frac{C}{N}\right)_{IM}$ is increasing. This is reprensatative of the trade off between power delivered by the TWT and intermodulation noise.

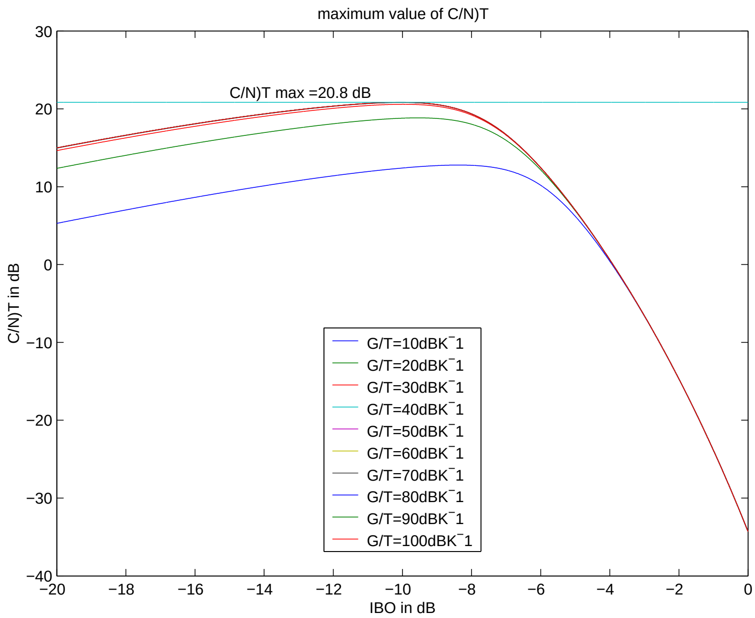
2.9 Minimum $\left(\frac{G}{T}\right)_{ES}$ values

We serch the minimum $\left(\frac{G}{T}\right)_{ES}$ to obtain the required value of $\left(\frac{C}{N}\right)_T$.
From the figure below, we deduce :

$$\begin{cases} \left(\frac{G}{T}\right)_{ES_{M=0dB}} = 9.5dB \\ \left(\frac{G}{T}\right)_{ES_{M=2dB}} = 12dB \end{cases}$$



2.10 Largest $\left(\frac{C}{N}\right)_T$



Even if $\left(\frac{G}{T}\right)$ increases, there is still interferences and intermodulation.

As $\left(\frac{C}{N}\right)_T^{-1} = \left(\frac{C}{N}\right)_U^{-1} + \left(\frac{C}{N}\right)_D^{-1} + \left(\frac{C}{N}\right)_I^{-1} + \left(\frac{C}{N}\right)_{IM}^{-1}$, if $\left(\frac{G}{T}\right)$ is very high, $\left(\frac{C}{N}\right)_D^{-1}$ is neglictable. So, there is a maximum value of $\left(\frac{C}{N}\right)_T$ which corresponds to $\left(\frac{C}{N}\right)_{T_{max}} = 20.8dB$.

3 Relationship between $(EIRP)_{ES}$ and $\left(\frac{G}{T}\right)_{ES}$

3.1 $(EIRP)_{ES}$ as a function of IBO

$$(EIRP)_{ES} = \frac{L_{FS}}{G_{Rx_{Sat}}} \cdot P_i^3 = \frac{L_{FS}}{\left(\frac{G}{T}\right)_{SL}} \cdot \frac{P_i^3}{(P_i^1)_{sat}} \cdot \frac{(P_i^1)_{sat}}{T} = \underbrace{\frac{L_{FS}}{\left(\frac{G}{T}\right)_{SL}} \cdot \frac{(P_i^1)_{sat}}{T}}_{A_{ES}} \cdot IBO$$

Hence A_{ES}, which represents the value of $EIRP$ when the satellite TWT is at saturation, is defined by :

$$A_{ES} = \frac{L_{FS}}{\left(\frac{G}{T}\right)_{SL}} \cdot A_U \cdot B_N k$$

Using the result of question 2.4, we deduce the diameter of the earth station antenna, calculated at f_{max} in order to always fulfil the minimal θ_{3dB} :

$$D_{SL_{Rx}} = \frac{70 \cdot c}{f_{uplink_{max}} \cdot \theta_{3dB}} = 0.53m$$

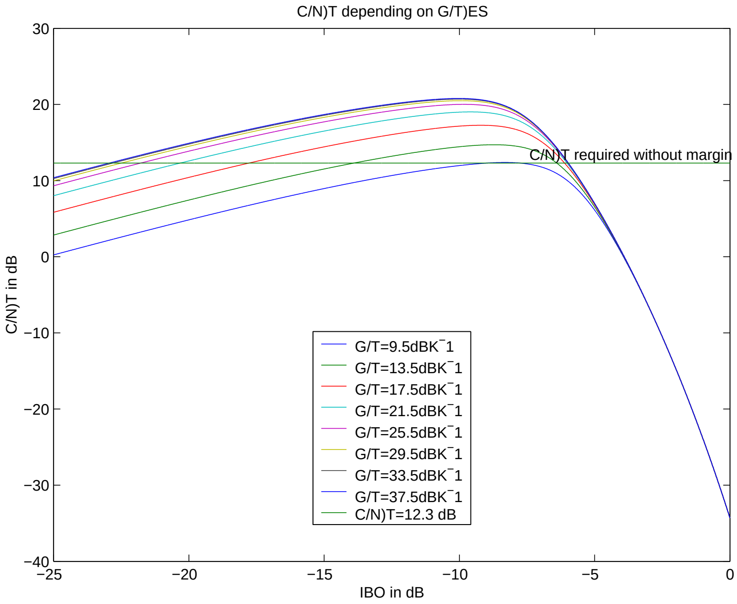
As A_{ES} must be minimized,

$$G_{SL_{ant}} = \eta_{Tx} \left(\frac{\pi D f_{max}}{c}\right)^2 = 34.7dB$$

$$\begin{cases} G_{SL} = \frac{G_{SL_{ant}}}{L_{FRX_{SL}}} \\ T_{U_{SL}} = 829K \end{cases} \Rightarrow \left(\frac{G}{T}\right)_{SL} = 4.4dB \cdot K^{-1}$$

So we get $A_{ES} = 79.4dBW$.

3.2 Minimum values of $(EIRP)_{ES}$



The minimum IBO to fulfil the mission is the abscisse of the intersection point between $\left(\frac{C}{N}\right)_{required}$ and $\left(\frac{C}{N}\right)_{T}$. When we have the minimum IBO, we could easily deduct the minimum $EIRP$ and fill the following array.

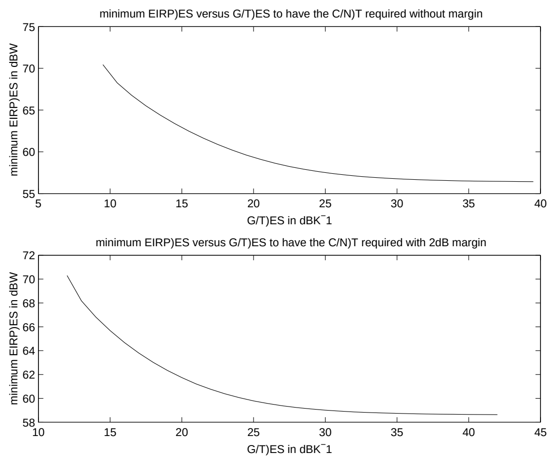
$\left(\frac{G}{T}\right)_{ES}$ in $dB \cdot K^{-1}$	IBO_{min} in dB	$EIRP_{min}$ in dBW
9.5	-9	70.4
13.5	-15	64.4
17.5	-18.5	60.9
21.5	-20.8	58.6
25.5	-22.0	57.4
29.5	-22.6	56.8
33.5	-22.9	56.5
37.5	-23.0	56.4

TAB. 3 – Minimum values of $(EIRP)_{ES}$ with $0dB$ margin

$\left(\frac{G}{T}\right)_{ES}$ in $dB \cdot K^{-1}$	IBO_{min} in dB	$EIRP_{min}$ in dBW
12	-9.1	70.3
16	-14.7	64.7
20	-17.7	61.7
24	-19.3	60.1
28	-20.2	59.2
32	-20.5	58.9
36	-20.7	58.7
40	-20.8	58.6

TAB. 4 – Minimum values of $(EIRP)_{ES}$ with $2dB$ margin

3.3 $(EIRP)_{ES}$ versus $\left(\frac{G}{T}\right)_{ES}$



4 Cost effective design of the earth station

4.1 G_T and tracking system

Three types of tracking systems are available : FMA, ATA step track or ATA monopulse.

- FMA : the parameter $a = SKW\sqrt{2} + SPU$ refers to the uncertainty of the satellite location seen from the earth station, with $SPU = 0.02^\circ$ and $SKW = 0.05^\circ$ seen from the center of the earth. So, $a = 0.09^\circ$ and $b = 0.2$ (θ_{3dB}).

$$G_{T_{FMA}} = \eta_{Rx} \left(\frac{\pi D f}{c}\right)^2 \cdot 10^{-1.2\left(b+\frac{aDf}{70c}\right)^2}$$

Tracking system	Fixed mount antenna		Step track antenna		Mono pulse antenna	
Diameter (m)	G_{Tx} (dB)	Cost(k\$)	G_{Tx} (dB)	Cost(k\$)	G_{Tx} (dB)	Cost(k\$)
2	44.2	2.4	44.9	21.1	45.4	61.1
3	47.2	7.0	48.4	27.0	48.9	67.0
4	49.1	14.7	50.9	35.7	51.4	75.7
5	50.4	26.3	52.9	48.1	53.3	88.1
6	51.3	42.2	54.4	64.7	54.9	104.7
7	51.9	63.0	55.8	86.1	56.2	126.1
8	52.2	89.1	56.9	112.8	57.4	152.8

- ATA step track : $b = 0.2$ (θ_{3dB})

$$G_{T_{ATA_{step\ track}}} = \eta_{Rx} \left(\frac{\pi D f}{c}\right)^2 \cdot 10^{-1.2b^2}$$

- ATA monopulse : $b = 0.1$ (θ_{3dB})

$$G_{T_{ATA_{step\ track}}} = \eta_{Rx} \left(\frac{\pi D f}{c}\right)^2 \cdot 10^{-1.2b^2}$$

4.2 Cost of the antenna as a function of G_T

From C_{Ant} function of D_{ES} and from the previous definitions of G_T, we derive C_{Ant} as a fonction of G_T, at f_{min} since the cost of the system is defined for f_{min} up to f_{max} and $C(G_T)$ is maximum at f_{min} :

- FMA : C_{FMA} is not deducable from $G_{T_{FMA}}(T)$ which is not reversable. A interpolation based on a finite number of values constitute the curve.

- ATA step track :

$$C_{step\ track} = 0.4 \cdot \left(\frac{c}{\pi f}\right)^{2.6} \left(G_T \cdot 0.5 \cdot 10^{0.048}\right)^{1.3} + 16.6 \cdot \left(\frac{c}{\pi f}\right)^{0.17} \left(G_T \cdot 0.5 \cdot 10^{0.048}\right)^{0.085}$$

- ATA monopulse :

$$C_{monopulse} = 0.4 \cdot \left(\frac{c}{\pi f}\right)^{2.6} \left(G_T \cdot 0.5 \cdot 10^{0.012}\right)^{1.3} + 16.6 \cdot \left(\frac{c}{\pi f}\right)^{0.17} \left(G_T \cdot 0.5 \cdot 10^{0.012}\right)^{0.085} + 40$$

4.3 Curves cost versus gain and type of tracking system

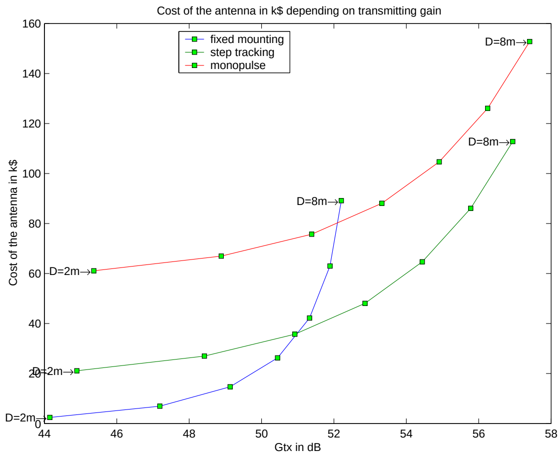


FIG. 4 – Cost versus gain

For antenna diameter smaller than $5m$, a fixed mount antenna is the cheaper tracking system. For higher antenna diameter, step tracking is better since it provides at a comparative price much better performances. Hence, we will choose fixed antenna when $D < 5m$ and ATA ST when $D > 5m$.

4.4 $\left(\frac{G}{T}\right)_{ES}$ as a function of diameter D_{ES} and type of tracking

Since the pointing of the antenna is done in receive mode, we take care to use η_{rx} and to take $L_{FRx_{ES}}$ into account.

$$\left(\frac{G}{T}\right)_{ES} = G_T \cdot \frac{1}{L_{FRx_{ES}}} \cdot \left(\frac{1}{T}\right)_{ES}$$

In clear sky conditions, earth station system noise is derived from :

$$T_{ES} = \frac{T_{Ant}}{L_{FRx_{ES}}} + T_F\left(1 - \frac{1}{L_{FRx_{ES}}}\right) + T_{Rx}$$

$$\begin{cases} T_{Ant} = T_{Ground} + T_{Sky}(elevation = 30^\circ) = 50K + 10K = 60K \\ L_{FRx_{ES}} = 0.2dB \\ T_F = 290K \\ T_{Rx} = 120K \end{cases} \Rightarrow T_{ES} = 190.3K$$

Tracking system	Fixed mount antenna		Step track antenna		Mono pulse antenna	
Diameter (m)	G_R	G/T (dBK^{-1})	G_R	G/T (dBK^{-1})	G_R	G/T (dBK^{-1})
2	44.1	21.1	44.7	21.7	45.1	22.1
3	47.3	24.3	48.2	25.2	48.6	25.6
4	49.3	26.4	50.7	27.7	51.1	28.1
5	50.8	27.8	52.7	29.7	53.0	30.0
6	51.8	28.8	54.2	31.3	54.6	31.6
7	52.6	29.6	55.6	32.6	55.9	33.0
8	53.1	30.1	56.7	33.8	57.1	34.1

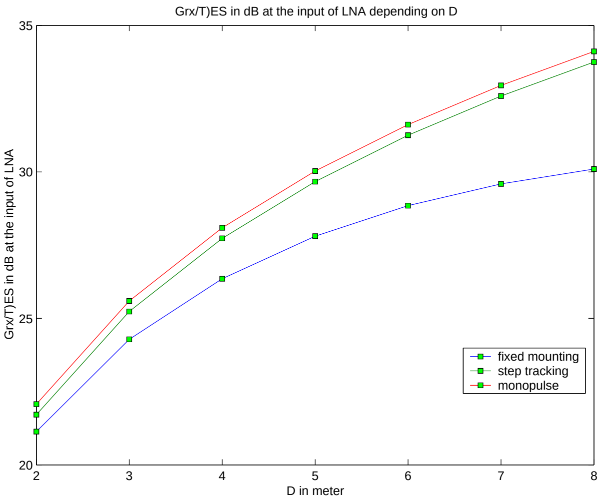


FIG. 5 – $\left(\frac{G}{T}\right)_{ES}$ versus diameter

4.5 Required power values per carrier

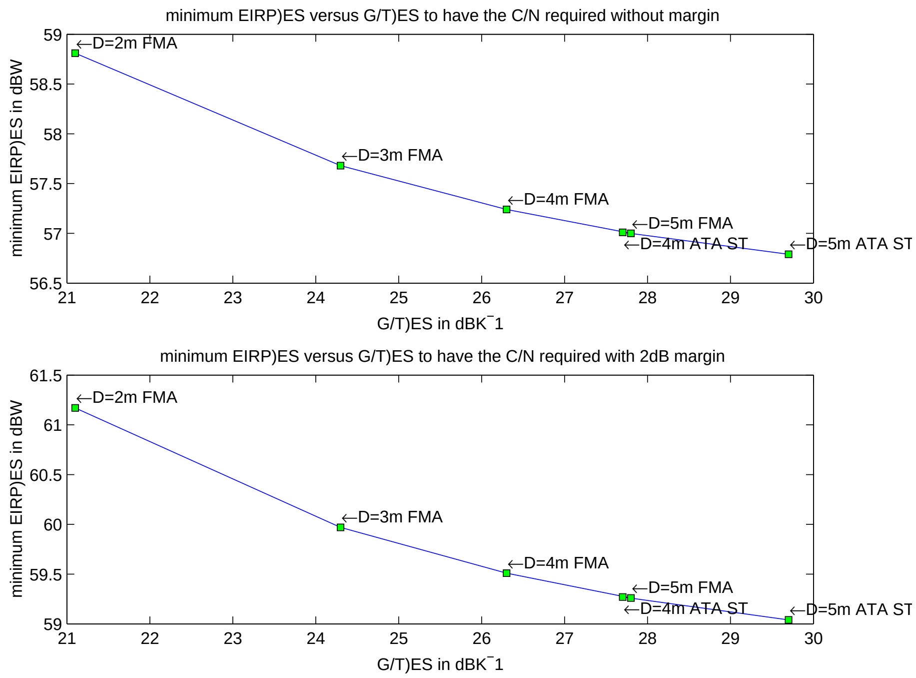


FIG. 6 – Minimum $(EIRP)_{ES}$ versus $\left(\frac{G}{T}\right)_{ES}$

4.6 Station RF equipments architecture

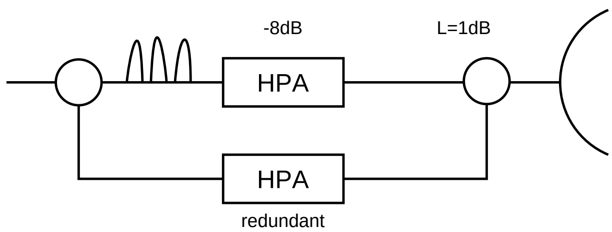


FIG. 7 – Pre-amplification case : $P_{hpa} = P_T + 8 + 1 + 10 \cdot log(3)$, $Cost = 2.5 \cdot C_{hpa}$

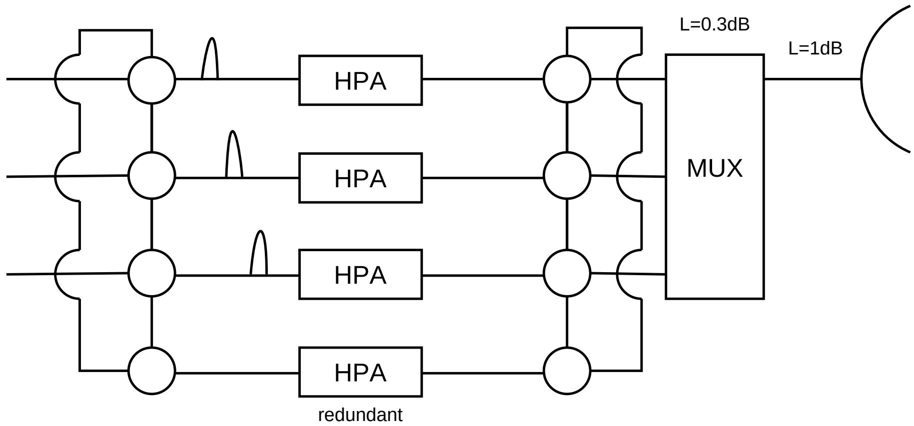


FIG. 8 – Post-amplification case : $P_{hpa} = P_T + 1.3$, $Cost = 4.75 \cdot C_{hpa}$

4.7 Power and cost of the HPA

$D(m)$	$G_T(dBi)$	$G_R(dBi)$	$\left(\frac{G}{T}\right)_{ES}(dB \cdot K^{-1})$	$EIRP_{ES}(dBW)$	$P_T(dBW)$
$2m$ FMA	44.2	44.1	21.1	58.8	14.6
$3m$ FMA	47.2	47.3	24.3	57.7	10.5
$4m$ FMA	49.1	49.3	26.3	57.2	8.15
$5m$ FMA	50.4	50.8	27.8	57.0	6.6
$4m$ ATA | ST	50.9	50.7	27.7	57.0	6.1
$5m$ ATA | ST	52.9	52.7	29.7	56.8	3.9

$D(m)$	C_{ant} $(k\$)$	P_{hpa} (W)	C_{hpa} $(k\$)$			C_F min $(k\$)$
			SSPA	TWT	Klystron	
2m FMA pre ampli	2.4	688.8	*135.9*	215.4	79.5	81.9
2m FMA post ampli		39.0	81.9	129.7	*113.3*	84.3
3m FMA	7	266.1	*92.9*	147.2	*72.3*	154.2
		15.1	56.0	88.7	*103.0*	63.0
4m FMA	14.7	155.3	*74.9*	118.7	*68.5*	133.4
		8.8	45.1	*71.5*	*97.6*	**59.8**
5m FMA	26.3	108.9	*65.0*	103.0	*66.1*	129.3
		6.2	39.1	*62.0*	*94.2*	65.4
4m ATA | ST	35.7	97.3	*62.1*	98.4	*65.4*	134.1
		5.5	37.4	*59.3*	93.2	73.1
5m ATA | ST	48.1	58.4	50.6	80.2	*62.1*	128.3
		3.3	30.5	*48.3*	*88.5*	78.6

4.8 Main characteristics of the earth station

		without margin	with 2dB margin
Antenna	Diameter(m)	4.0	4.0
	Type of tracking	FMA	FMA
	G_T (dBi)	50.9	50.9
	C_{ant} $(k\$)$	14.7	14.7
HPA	$P_{hpa}(W)$	8.8	14.7
	Technology	SSPA	SSPA
	Mode of RF coupling	post amplification	post amplification
	C_{hpa} $(k\$)$	45.1	55.6
	P_T (dBW)	8.1	10.4
Total cost	C_F $(k\$)$	59.8	70.3
Link budget	$EIRP$ (dBW)	57.2	59.5
	G/T (dBK^{-1})	26.3	26.3
	IBO (dB)	-22.2	-19.9
	OBO (dB)	-16.7	-14.6
	$(C/N)_U$ (dB)	13.5	15.8
	$(C/N)_D$ (dB)	20.1	22.2
	$(C/N)_{IM}$ (dB)	34.0	29.7
	$(C/N)_I$ (dB)	23.2	23.2
	$(C/N)_T$ (dB)	12.3	14.3

4.9 Characteristics of the earth station with $2dB$ margin

The additional cost of a $2dB$ margin is $10,5k\$$ for one station. But we need to keep in mind that this extra cost must be multiplied by the number of stations. So we will have an extra cost of $24 \cdot 10,5k\$ = 252k\$$!

$D(m)$	$G_T(dBi)$	$G_R(dBi)$	$\left(\frac{G}{T}\right)_{ES}(dB \cdot K^{-1})$	$EIRP_{ES}(dBW)$	$P_T(dBW)$
$2m$ FMA	44.2	44.1	21.1	61.2	17.0
$3m$ FMA	47.2	47.3	24.3	60.0	12.8
$4m$ FMA	49.1	49.3	26.3	59.5	10.4
$5m$ FMA	50.4	50.8	27.8	59.3	8.9
$4m$ ATA | ST	50.9	50.7	27.7	59.3	8.4
$5m$ ATA | ST	52.9	52.7	29.7	59.0	6.1

$D(m)$	C_{ant} $(k\$)$	P_{hpa} (W)	C_{hpa} $(k\$)$			C_F min $(k\$)$
			SSPA	TWT	Klystron	
2m FMA pre ampli	2.4	1186.1	*168.9*	267.7	83.9	86.3
2m FMA post ampli		67.1	*101.7*	161.2	*119.6*	163.6
3m FMA	7	450.9	*114.7*	181.8	76.2	83.2
		25.5	69.1	109.5	108.6	76.1
4m FMA	14.7	261.9	*92.3*	146.3	*72.2*	161.0
		14.8	55.6	88.1	*102.9*	**70.3**
5m FMA	26.3	183.3	*80.0*	126.8	*69.6*	153.1
		10.4	48.2	*76.4*	*99.3*	74.5
4m ATA $\mid$ ST	35.7	163.7	*76.5*	121.2	*68.8*	156.9
		9.3	46.1	*73.0*	98.2	81.8
5m ATA $\mid$ ST	48.1	98.0	*62.3*	98.7	*65.4*	146.8
		5.5	37.5	*59.5*	*96.2*	85.6

5 Performance under rainy conditions

Under rainy conditions, the path loss increases with respect to the polarization and frequency of the signal. Moreover, the $\left(\frac{G}{T}\right)_{ES}$ is also modified, since rain contributes to the noise temperature of the earth station antenna.

5.1 Loss in rainy conditions

$A_{0.075}$ is the attenuation due to rain exceeded 0.3% of any month (hence 0.075% of the year). We compute $A_{0.075}$ at the maximum frequency of each third of the frequency plan because attenuation due to rain increases with frequency, and in both polarizations in order to inverse polarization if it is relevant. Values for the current frequency plan are in bold.

Earth station	Zone A				Zone B				Zone C			
f (GHz)	12.75	12.75	13.25	13.25	12.75	12.75	13.25	13.25	12.75	12.75	13.25	13.25
Polarization	V	H	V	H	V	H	V	H	V	H	V	H
$A_{0.075_{dB}}$	**2.5**	2.7	2.5	**2.8**	2.6	**2.8**	**2.7**	2.9	**1.6**	1.7	1.7	**1.8**
f (GHz)	11.53	11.53	11.7	11.7	11.36	11.36	11.7	11.7	11.36	11.36	11.53	11.53
Polarization	V	H	V	H	V	H	V	H	V	H	V	H
$A_{0.075_{dB}}$	**2.2**	2.4	2.3	**2.5**	2.3	**2.5**	**2.4**	2.5	**1.5**	1.5	1.5	**1.6**

We notice there is more attenuation in horizontal polarization than in vertical polarization. In uplink, the worst attenuation is $2.8dB$ while in downlink, it is $2.5dB$.

5.2 Antenna noise in rainy conditions

In rainy conditions, antenna noise temperature is derived from :

$$T_{Ant} = \frac{T_{Sky}}{A_{Rain}} + T_m \left(1 - \frac{1}{A_{Rain}}\right) + T_{Ground}$$

The value used for A_{Rain} is the worst $A_{0.075_{dB}}$ in downlink (when the earth station receives signal), i.d. $2.5dB$. As $T_m = 1.12 T_{amb} - 50$, we consider $T_{amb} = 290K$ thus $T_m = 275K$. Hence, we get $T_{Ant} = 176K$.

By using the same formula as in 4.4 with the T_{Ant} specific to rainy conditions, we find $T_{ES} = 301K$, i.d. $2dB$ more noisy than in clear sky conditions. That implies a $\left(\frac{G}{T}\right)_{ES}$ $2dB$ smaller with rain.

5.3 Offered $\left(\frac{C}{N}\right)_T$ in rainy conditions

Since the earth station emits at the same power level whatever are the weather conditions, the loss due to rain translates in uplink as a lower IBO ($-2.9dB$) and in downlink as a larger L_D ($+2.5dB$).

	without margin	with 2dB margin
$EIRP$ (dBW)	57.2	59.5
G/T (dBK^{-1})	24.3	24.3
IBO (dB)	-25.0	-22.7
OBO (dB)	-19.3	-17.2
$(C/N)_U$ (dB)	10.7	13.0
$(C/N)_D$ (dB)	13.0	15.1
$(C/N)_{IM}$ (dB)	39.4	35.0
$(C/N)_I$ (dB)	23.2	23.2
$(C/N)_T$ (dB)	8.5	10.7

5.4 Required $\left(\frac{C}{N}\right)_T$ in rainy conditions

In the same way we calculated the required $\left(\frac{C}{N}\right)_T$ in clear sky conditions in questions 1.6 and 1.7, we get : $S_{test\ tone}$=1 mW and the 50000 $pWOp$ noise, included 2500 $pWOp$ for other sources of noise.

$$\frac{S}{N} = \frac{1\ mW}{47500\ pW}\ ;\ \left(\frac{S}{N}\right)_{dB} = 43.3\ dB$$

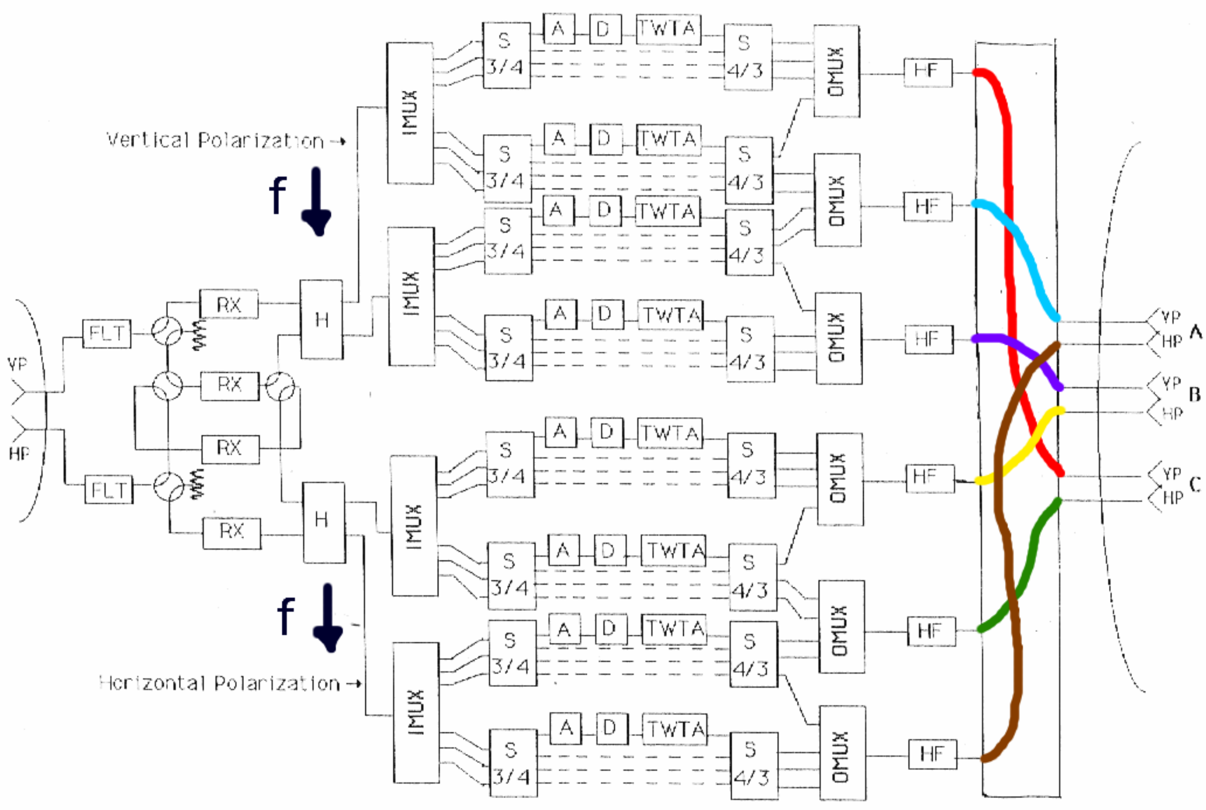
$$\left(\frac{C}{N_0}\right)_T (dB) = 74.7\ dBHz \Rightarrow \left(\frac{C}{N}\right)_T (dB) = 4.3\ dB$$

Since the demodulator thresold is $7dB$, this is the effective required $\left(\frac{C}{N}\right)_T$. Indeed, if the demodulator thresold was not reached, there would be no communications at all.

The offered $\left(\frac{C}{N}\right)_T$ in rainy conditions, either $8.5dB$ or $10.6dB$ depending on the margin, is higher than the demodulator thresold.
The actual design fulfils requirements even in rainy conditions. Moroever, we notice that by inverting the polarization of the frequency plan, since the worst attenuation due to rain in uplink would change from $2.8dB$ to $2.9dB$, while the one in downlink would remain the same, i.d. $2.5dB$.

6 Design of the communications payload

We consider the lower frequencies on the top of the figure and higher ones at the bottom.



7 Upgrade to digital transmission

If we keep the same characteristics for the station as in question 4.8 we obtained with array knowing that the total network capacity is

$$\begin{cases} R_c = \sigma \cdot B = 16.2Mbit/s \ with \ B = 10,8MHz \\ R_b = \rho \cdot R_c \\ \left(\frac{C}{N_o}\right)_{req} = \left(\frac{E_b}{N_o}\right)_{\rho} \cdot \rho \cdot \sigma \cdot B \\ \left(\frac{C}{N}\right)_{req} = \left(\frac{E_b}{N_o}\right)_{\rho} \cdot \rho \cdot \sigma \end{cases}$$

The total Network capacity is $C_t = \frac{0{,}95 \cdot R_b \cdot 72}{64 \cdot 10^3}$.

ρ	$\frac{E_b}{N_o}$ required (dB)	$\frac{C}{N}$ required (dB)	Margin (dB)	Network capacity (voice channels)
1	10.5	12.3	0.5	17314
7/8	7.3	8.5	3.3	15150
3/4	6	6.5	5.3	12985
1/2	5.2	4	7.8	8657
1/3	4.7	1.7	10.1	5771

TAB. 5 – Clear sky condition $BER = 10^{-6}$

ρ	$\frac{E_b}{N_o}$ required (dB)	$\frac{C}{N}$ required (dB)	Margin (dB)	Network capacity (voice channels)
1	8.4	10.2	-2.2	17314
7/8	6	7.2	0.8	15150
3/4	4.7	5.2	2.8	12985
1/2	3.8	2.6	5.4	8657
1/3	3.4	0.4	7.6	5771

TAB. 6 – Rainy condition $BER = 10^{-4}$

Assuming that the $\left(\frac{C}{N}\right)_T$ of the link budget will be decrease of $0,5dB$ with the degradation due to the demodulator.

We have a link budget :

- In clear sky condition without margin : $\left(\frac{C}{N}\right)_T$=11.8dB
- In rainy condition without margin : $\left(\frac{C}{N}\right)_T$=8dB

If we want to keep the characteristics of the question 4.8, we need to add coding to fulfil the mission. We will choose a ρ factor of 7/8 to fulfil the mission with keeping a quite good network capacity.

Antenna diameter (m)	4
Transmitted power per carrier (W)	8.1
Power of transmitted amplifier (W)	8.8
Cost function C_F ($k\$$)	59.5
Coding rate	7/8
Margin in clear sky condition (dB)	3.3
Margin in rainy condition (dB)	0.8
Network Capacity (voice channel)	15150

By using DCME (Digital Circuit Multiplication Equipment), a compression factor of 5 : 1 applies on trafic, and thus the network capacity is improved by a factor of 5.

Even if the impact of digitalization on the cost of the network system and customers devices has to be taken into account, the network capacity can be hugely improved, thanks to more effective modulation and digital compression schemes.

Air interface	Network capacity (voice channels)
FDM / FM / FDMA	13284
TDM / QPSK / FDMA	15150
TDM / QPSK / FDMA with DCME	75750