LELEC2910 : Project report

Calculation of the effect of the troposphere on the Alphasat satellite payload and future W band systems

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Antennas and Propagation

Contents

1 Introduction

In order to increase bandwidth of data transmission, higher frequency band are considered nowadays. Along with this, the MetOp second generation satellite will download data in the 26GHz. To go further, spatial agencies and firms linked to them foresee to use even higher frequencies. These frequencies are located between 76 and 90 GHz which is the next window in the attenuation spectrum after the one around 26GHz. In this perspective, ESA has launched the project of creating a new W-band Cubesat at 76GHz.

While using these frequencies problems arise because the attenuation due to tropospheric effects (gases, clouds and rains) become important as displayed by the dark-blue arrow in figure 1. On top of that, available models (from the ITU) are knwon to be accurate only up to 50 GHz, new measurement are then needed.

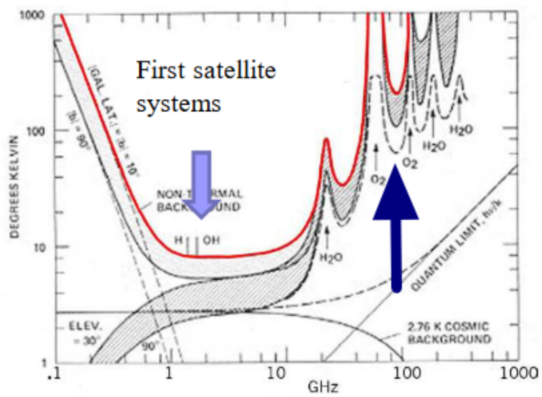


Figure 1: Attenuation Spectrum, the dark-blue arrow displaying the bandwidth used for the project

This report aim to study tropospheric effect on trasmission at 75GHz and calculate the link budget to evaluate the EIRP of the Cubesat. We will also need another frequency, 37.5GHz, because our Cubesat is non-geostationnary (2800 km), it will then enable to verify the non-GEO models. Experimentation are carried out at two different receiving earth stations.

This project, being analogous to the one realized in the course LELEC2795, a part of the explanation of the different attenuation will be taken from the report concerning Rapids simulation realized for this course.[1] But it will be substantially different because two base station will be compared at the same time. Each with their own characteristics.

2 The two receiving earth stations

2.1 Louvain-La-Neuve

Location	Latitude	Longitude	above mean sea level
Louvain-La-Neuve, Belgium	50.668°N	4.615°E	160m

Figure 2: Louvain-La-Neuve station localization

The Louvain-La-Neuve antenna diameter is 1.2 m. The localization on the earth can be seen on figure 3.

[1]The co-author of the LELEC2795 report are Thibault Fievez and Alexandre Fiset.

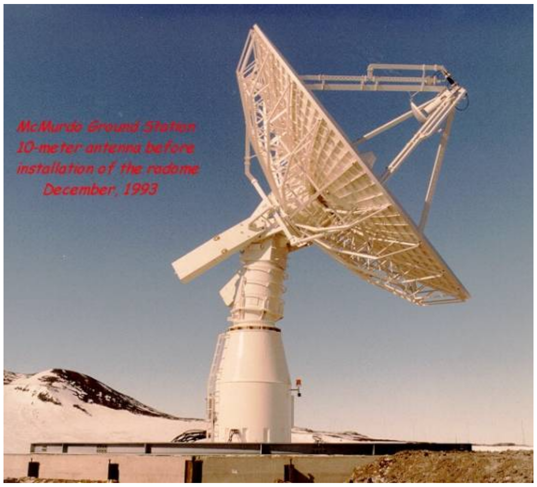
Figure 3: Example on a receiving antenna at McMurdo Station

2.2 McMurdo

Location	Latitude	Longitude	above mean sea level
McMurdo, Antartica	-77.846°N	166.68°E	150m

Figure 4: McMurdo station localization

A typical antenna installed at McMurdo station can be seen on figure 5.[1] [2] This antenna has a 10 m diameter. Even is the station is located on the shore, the antennas are installed a bit higher on the hills surrounding the station, at 150m above the sea level.



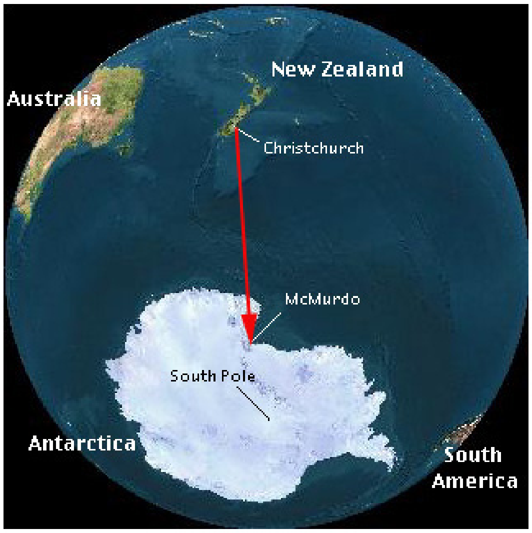


Figure 5: On the left, example of a receiving antenna at McMurdo Station. On the right the localization of the station on the earth.

3 Total attenuation and various components

3.1 Total attenuation

The total attenuation increases for higher frequencies signals as well as for lower elevation angles, as showcased on the graphs of figure 6[2]. In general, higher frequency signals are more prone to water based attenuation. This graph includes the attenuation due to gazes, clouds, rain and scintillation.
It is straightforward to see that the attenuation for Louvain-La-Neuve is higher than the one for McMurdo. We have three particular features:

- the total attenuation for Louvain-La-Neuve typically varies from several decade of dB up to a bit more than 100 dB (107dB in the worst case).
- the total attenuation for McMurdo typically varies from one to several dB (9 dB in the worst case).
- The power (or EIRP) needed to correctly transmit data to McMurdo station will be much less than for Louvain-La-Neuve (this anticipated result will be later shown analytically).

The approach followed on this report will be to isolate the attenuation from the different sources, identify their causes, characterize their level and compare between the stations. The result expected for the different contribution in the total attenuation should be globally similar to figure 7.

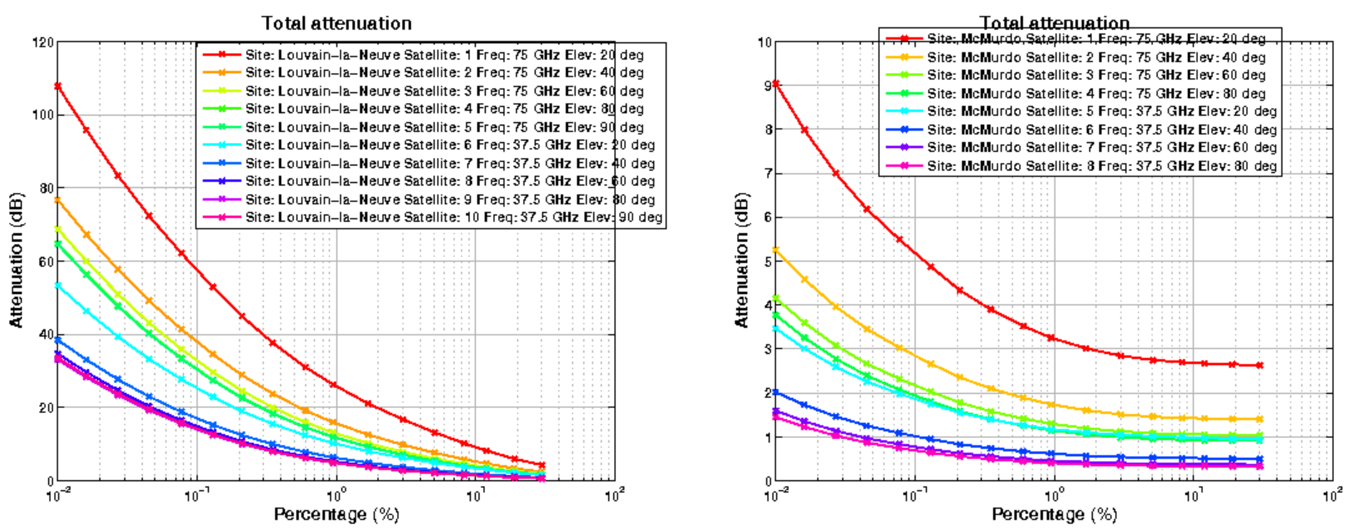


Figure 6: The left figure displays the CCDF of total attenuation for Louvain-La-Neuve base station. The right one shows the total attenuation for McMurdo

[2]Right graph taken from LELEC2910-Antennas and Propagation, Christophe Craeye and Danielle Janvier

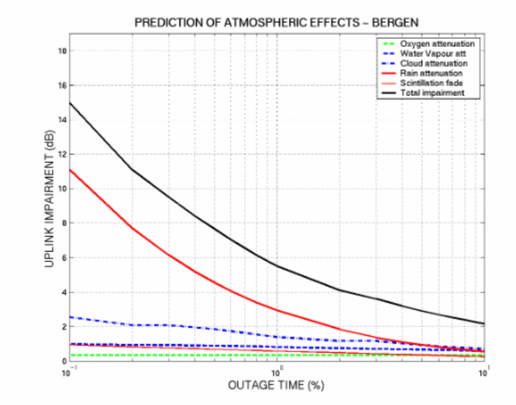


Figure 7: Example of the different contribution to the attenuation taken from the course

3.2 Clouds

As one can observe in figure 9 and 10, the curve of the attenuation due to clouds is strongly linked to the curve of the water content. This is expected from the theory because the attenuation due to clouds is proportional to the water content (g/m^3) in clouds, the value of L varies depending on the position on the earth. [3] An example of the values taken are shown on figure 11 (our two base station in red). We can observe several features:

- for Louvain-La-Neuve, the attenuation for clouds varies from 0 dB up to several dB (close to 20 in the worst case) whereas for Mc Murdo this attenuation takes only values between 0 and 0.9 dB. Then, McMurdo's attenuation is way below the one at Louvain-La-Neuve.
- the level of attenuation strongly increases with frequency. The wavelength becoming smaller the effect of interactions with water molecules increases.
- the attenuation decreases with the elevation angle this is expected because this implies lower reflexions

The observation above are validated by/also seen through the formula:

$$A(P) = \frac{L(P)\,K_l}{\sin \alpha_1}$$

$$K_l = \frac{0.819 f}{\varepsilon''(1+\eta^2)} \qquad \text{(dB/km)/(g/m}^3\text{)}$$

$$\eta = \frac{2+\varepsilon'}{\varepsilon''}$$

The dielectric permittivity of water is given in the recommendation

Figure 8: Formula for cloud attenuation

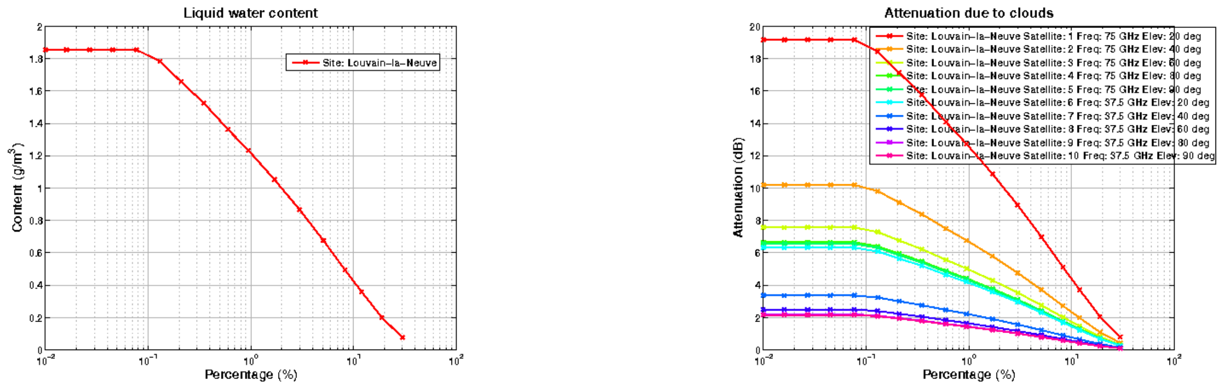


Figure 9: Louvain-La-Neuve station-Liquid water content is displayed on the left while on the right another graph shows the attenuation due to clouds

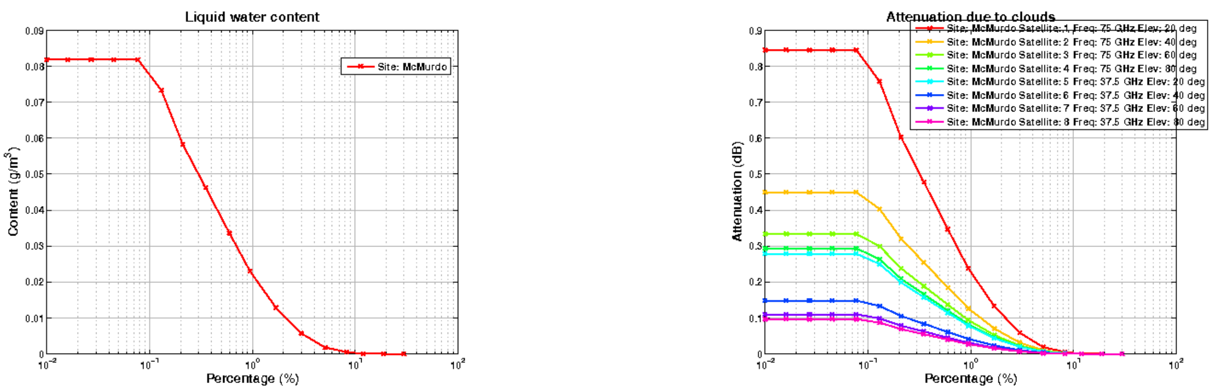


Figure 10: McMurdo station-Liquid water content is displayed on the left while on the right another graph shows the attenuation due to clouds

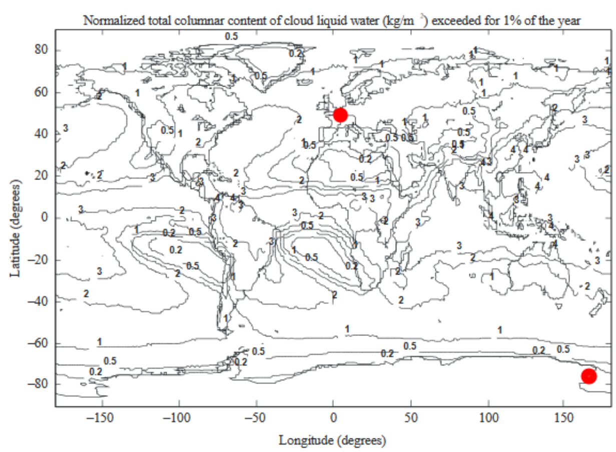


Figure 11: Normalized total columnar liquid water exceeded for 1% of the year. In red our base station with different values given by the contour. A smaller value is oberserved for the McMurdo Station

3.3 Rain

Figure 12 represent the attenuation due to rain. We can deduce some features from this graph:

- for Louvain-La-Neuve, this attenuation varies from several dB up to 90 dB (the 90 dB will occur 0.01% of the year for 75 GHz it is the worst case). For Mc Murdo this attenuation is much smaller, it varies from 0 to a bit less than 6 dB, it is several time smaller for Mc Murdo than for Louvain.
- it is the most subtantial attenuation.
- the lower the percentage is, the more it takes into account rarer effects such as heavier rain with big rain drop and then implies higher attenuation

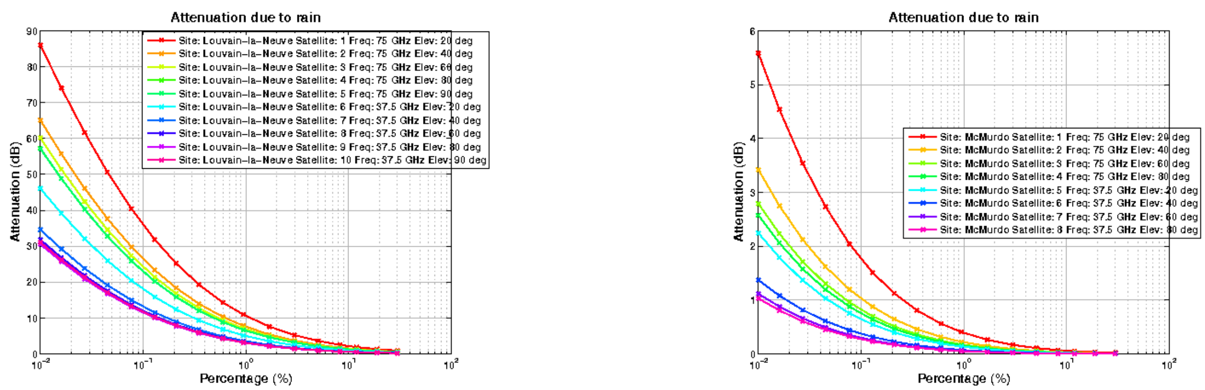


Figure 12: Attenuation due to rain for Louvain-La-Neuve on the left and for McMurdo on the right

3.4 Gases and water vapor

Our signals travelling through the troposphere the absorption on the left in figure 13[3] at 37.5 GHz and 75 GHz must be multiplied by the number of kilometers it has traveled through gases to obtain the real absorption from which we can deduce the attenuation. This absorption is almost constant through the entire year. The right graph of figure 13 shows the total attenuation due to gases for a particular frequency. Even if this is not a frequency used in this report the contour don't vary much compare to for 37.5 and 75 GHz. Clearly Mc Murdo, located in the white region, is less affected than Louvain. Globally this attenuation is very low.

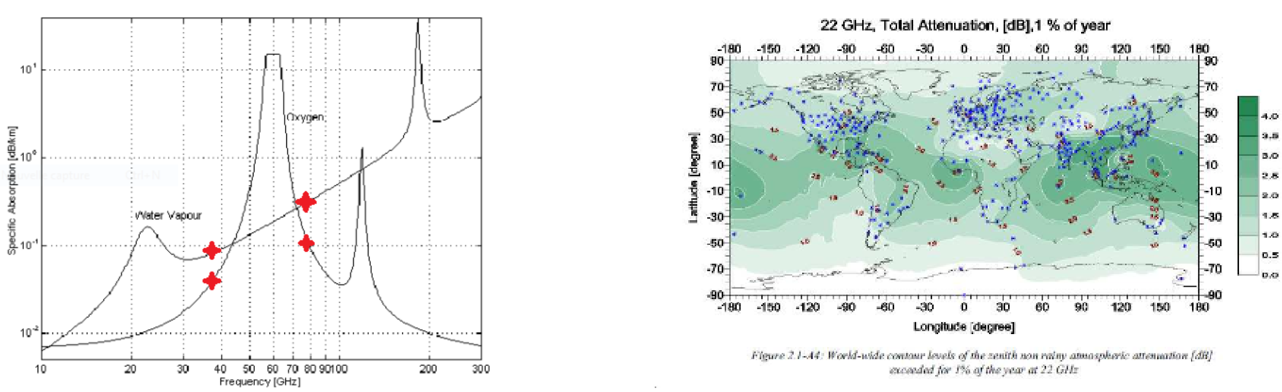


Figure 13: On the left, typical absorption per Km for water vapor and oxygen through the troposphere. On the right an example of total attenuation due to gases

[3]Taken from LELEC2910-Antennas and Propagation, Christophe Craeye and Danielle Janvier

3.5 Scintillation

Scintillation due to turbulences is an effect experienced by waves propagating through troposphere. This causes quick temporal variation in the signal's amplitude and phase. This effect is highlighted in figure 14. The origin of this natural phenomenon are small but random atmospheric temperature fluctuations. [4] This effect is lower for McMurdo than for Louvain, this means that polar skies are less subject to tropospheric turbulences[4]. We also see for McMurdo that this effect doesn't depends on the frequency but only the angle.

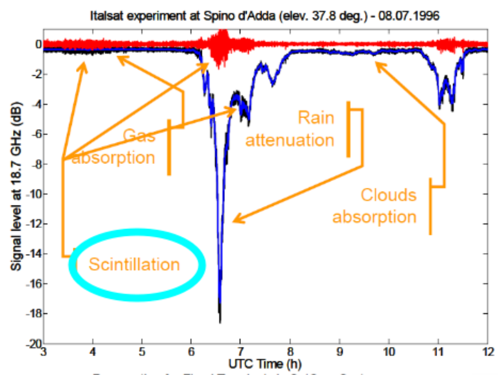


Figure 14: Temporal signal and the various attenuation. Scintillation is circled in cyan

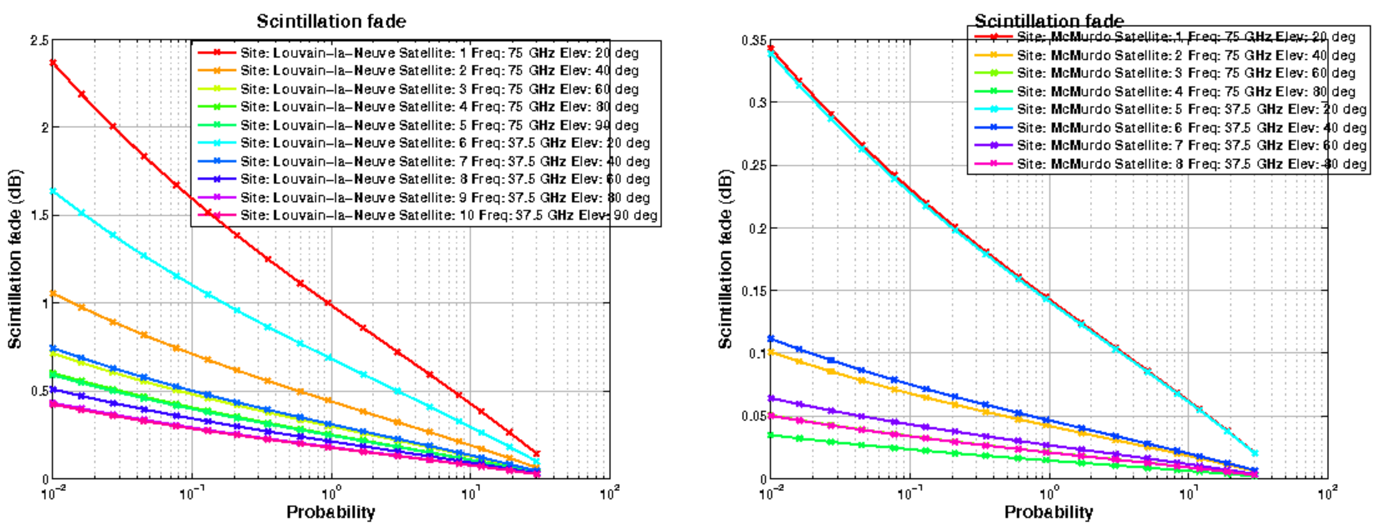


Figure 15: The left figure displays the attenuation due to scintillation effect for the Louvain station while on the right it is shown for McMurdo

3.6 Graph conclusion

To conclude this part, it should be noticied than the rain contribution is the most important for both Louvain-La-Neuve and McMurdo. Attenuation due to gases is very small (close to 0 for McMurdo, and small for Louvain). Scintillation fade is low. But while attenuation du to clouds is very low for McMurdo it can be high for Louvain. For all the different attenuation McMurdo exhibits a lower fading.

[4]It would be completely different if ionospheric scintillations would be studied, because there are more charged particles at the poles due to the combination of magnetic field and solar emissions.

4 Link budget and EIRP

4.1 Equation and parameters

The receiver detection depends on the SNR at its entry. By fixing a required SNR for detection we then ensure the information are well received. To tune the satellite so that this SNR is reached we need to rewrite the equation of the link budget including the SNR. Then we can calculate the EIRP.

The specifications are given in figure 16

Earth-satellite mean distance: 2800 km	
W band	
frequency	75 GHz.
Polarization	Dual polarization (RHCP* and LHCP*)
Antenna boresight	Nadir
EIRP	?? dBW
Receive antenna gain	51 dBi
Antenna efficiency	57%
LNA noise temperature	500K
Receiver bandwidth	50 Hz
Min C/N for detection	10 dB
Q band	
frequency	39.5 GHz.
Q Band Polarization	Dual polarization (RHCP* and LHCP*)
Boresight	Nadir
EIRP	?? dBW
Receive antenna gain	To be evaluated, same antenna as for W band
Antenna efficiency	60%
LNA noise temperature	450K
Receiver bandwidth	50 Hz
Min C/N for detection	10 dB

Table 2: Main characteristics of the W-band Cubesat beacons

Figure 16: Characteristics of the W-band Cubesat beacons with a min C/N for detection

The useful formula is:

$$SNR = \frac{P_R}{N} = \frac{EIRP\ G_R}{NL} = \frac{EIRP\ G_R}{BN_0L} \tag{1}$$

Then the EIRP required is given by:

$$EIRP = \frac{SNR_{detect}\ NL}{G_R} \tag{2}$$

In dB:

$$EIRP[dBW] = SNR_{detect}[dB] + N[dB] + L_{FS} + L_{totAtt} - G_R[dB] \tag{3}$$

$$EIRP[dBW] = SNR_{detect}[dB] - G_R[dB] + 10\log(k_bBT) + 10\log\left[\left(\frac{4\pi d}{\lambda}\right)^2\right] + L_{totAtt}[dB] \tag{4}$$

4.2 The receive antenna gain

We need the missing G_R for the Q band. In order to calculate it we use the G_R for the W band because it is the same antenna then the physical are is the same.

$$G_R = 10\log(\frac{4\pi d}{\lambda^2}A\eta) \quad (5)$$

For 75 GHz: $\lambda = 4$ mm, $G_R = 51$ dBi, $\eta = 0.57$ gives A = 0.2812 m^2. Then for 37.5 GHz with $\lambda = 8$ mm, $\eta = 0.57$, A = 0.2812 m^2 the value of G_R is 45.202 dBi.

4.3 EIRP

All the parameters needed are available. Replacing them in equation 4 gives:

For 75 GHz:

$$EIRP[dBW] = 10 - 51 - 184.62 + 198.89 + L_{totAtt}[dB] \quad (6)$$

For 37.5 GHz:

$$EIRP[dBW] = 10 - 51 - 185.08 + 192.57 + L_{totAtt}[dB] \quad (7)$$

Here $L_{totAtt}[dB]$ is taken from the graph/datas of the total attenuation provided by Rapids. It is of course according to a particular availability of the station.

4.4 EIRP for an availability of the station 99.0, 99.5, 99.9 and 99.99% of the time

The attenuation for Louvain-La-Neuve are shown in figure 17 and for McMurdo in figure 18.

Total Attenuation for Louvain-La-Neuve station (dB)					
Frequency(GHz)	Elevation angle (°)	99%	99.5%	99.9%	99.99%
75	20	25,5	32	58	107,8
	60	12,5	17,5	33	68,8
37,5	20	10	13,5	25,3	53,3
	60	5,1	7	14,8	34,7

Figure 17: Values of the attenuation at Louvain-La-Neuve station

Total Attenuation McMurdo station (dB)					
Frequency(GHz)	Elevation angle (°)	99%	99.5%	99.9%	99.99%
75	20	3,21	3,65	5,2	9,04
	60	1,29	1,48	2,15	4,15
37,5	20	1,17	1,3	1,8	3,47
	60	0,45	0,52	0,77	1,59

Figure 18: Values of the attenuation at McMurdo station

The EIRP for Louvain-La-Neuve are then calculated in both dBW and W and displayed on figure 19. While the EIRP for McMurdo station is on figure 20.

EIRP for Louvain-La-Neuve station (dBW)					
Frequency(GHz)	Elevation angle (°	99%	99.5%	99.9%	99.99%
75	20	-1,23	5,27	31,27	81,07
	60	-14,23	-9,23	6,27	42,07
37,5	20	-16,73	-13,23	-1,43	26,57
	60	-21,73	-19,73	-11,93	7,97

EIRP for Louvain-La-Neuve station (W)					
Elevation angle (°)	Frequency(GHz)	99%	99.5%	99.9%	99.99%
20	75	0,753	3,37	1339,7	128 10^6
	37.5	3,78 10^-2	0,119	4,24	16106,5
60	75	2,12 10^-2	4,75 10^-2	0,719	454
	37.5	6,71 10^-3	0,011	0,064	0,16

Figure 19: EIRP for trasmission at Louvain-La-Neuve station in dBW and W

EIRP for McMurdo station (dBW)					
Frequency(GHz)	Elevation angle (°	99%	99.5%	99.9%	99.99%
75	20	-30,3	-29,86	-28,31	-24,47
	60	-32,22	-32,03	-31,36	-29,36
37,5	20	-32,34	-32,21	-31,71	-30,04
	60	-28,41	-32,99	-32,74	-31,92

EIRP for McMurdo station (dBW)					
Elevation angle (°)	Frequency(GHz)	99%	99.5%	99.9%	99.99%
20	75	9,3 10^-4	1,03 10^-3	1,48 10^-3	3,6 10^-3
	37.5	6 10^-4	6 10^-4	7 10^-4	1,16 10^-3
60	75	6 10^-4	6 10^-4	7 10^-4	1 10^-3
	37.5	1,44 10^-3	5 10^-4	7 10^-4	6 10^-4

Figure 20: EIRP for trasmission at Louvain-La-Neuve station in dBW and W

5 Analysis of the result and comments

As expected, the power required to perform data transmission at McMurdo station is several order of magnitude below the one required for good transmission at the Louvain station. For the McMurdo Station the required power (or EIRP) is always small, in the order of the mW. On the contrary, the Louvain-La-Neuve EIRP can take absurd values, particularly for very high availabilities (99.9% and 99.99%) and small angles (20°) as seen in figure 19.

The Cubsat being small, cheap satellites (this one is made of 2U) they are very limited on the power they used. The power storage occurs in batteries fed by photovoltaic cells, these have low efficiancy (around 30%). [5] On top of that power is consumed by onboard instruments. The power required to transmit the data then need to be minimized (in order to have more datas for the electronics used for measurements). In other words, a compromise is needed between power for data transmission and power for data measurements (example for the design of a 3U cubesat on figure 21 [6]). Because the 2U Cubesat specifications (particularly the on board Payload and about the solar cells) are unknown, the proposed EIRP is 5W or 7 dBW. Using this value, McMurdo station will be able to receive all the time while is is not the case for Louvain-La-Neuve, these limits are displayed in figure 22.

			Orbit		Eclipse	
	Power (W) each	Number Active	Avg Duty Cycle (%)	Watts	Avg Duty Cycle In Eclipse (%)	Watts
PAYLOAD						
Payload	2.1	1	100	2.1	100	2.1
			Total	2.1	Total	2.1
PLATFORM SUB-SYSTEMS						
Communications						
UHF TX	1.9	1	10	0.2	10	0.2
VHF RX	0.15	1	100	0.2	100	0.2
ADCS						
ADCS Board	0.1	1	100	0.1	100	0.1
Magnetorquers	0.1	1	2	0.0	2	0.0
Sensors	0.01	1	100	0.0	100	0.0
On-Board Data Handling						
OBC	0.25	1	100	0.3	100	0.3
Thermal Control System						
Battery Heaters	2	1	0	0.0	0	0.0
Power						
Power System Electronics	0.05	1	100	0.1	100	0.1
Platform Subtotal				0.8		0.8
Margin (platform and payload)				20%		20%
			Total	**3.4**	**Total**	**3.4**

Figure 21: Example of power specification for a 3U Cubesat [6]

EIRP for Louvain-La-Neuve station (W)					
Elevation angle (°)	Frequency(GHz)	99%	99.5%	99.9%	99.99%
20	75	0,753	3,37	1339,7	128 10^6
	37.5	3,78 10^-2	0,119	4,24	16106,5
60	75	2,12 10^-2	4,75 10^-2	0,719	454
	37.5	6,71 10^-3	0,011	0,064	0,16

Figure 22: For an EIRP of 5W (or 7dBW), in green the reachable availabilities, in red the unreachable ones

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