Satellite Communication

Project 3 - POLAR Satellite

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Chapter 1

General information

1.1 Polar Satellite

The POLAR satellite is one of the 4 spacecraft launched for the GGS program (Global Geospace Science) which are part of the six spacecraft of the ISTP program (International Solar Terrestrial Physics).

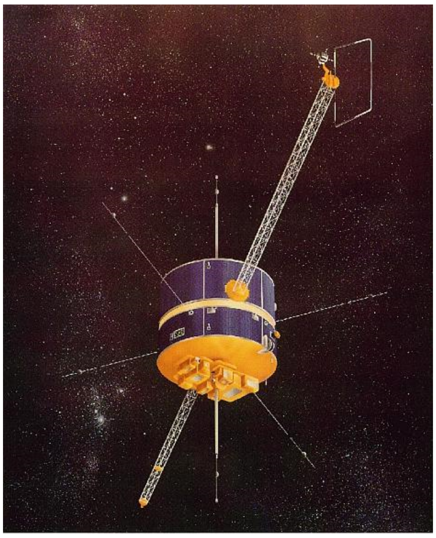

Figure 1.1: Polar Satellite

1.1.1 Mission and abilities

POLAR is able to get multi-wavelength vision from the aurora, it measures the plasma entry to the polar magnetosphere as well as the geomagnetic tail, the flow both ways to the ionosphere and the displacement of energy particles into the ionosphere and the higher atmosphere.

1.1.2 Orbit

POLAR has a 22hh and 36 mins polar orbit with an apogee of 57 000 km and a perigee of 11 500 km. It was launched in 1996 to observe the polar magnetosphere and later was used to observe the equatorial inner. As of 11th January 2019, the two line elements for POLAR (TLE) were :

1. POLAR,
2. 1 23802U 96013A 20007.96347079 .00000245 00000-0 00000+0 0 9998,
3. 2 23802 78.7065 252.0668 6485272 288.6366 14.7247 1.29845654114298

1.1.3 Technical properties

The POLAR satellite has a propulsion system and it is designed to have a lifetime of between 3 and 5 years and also has redundant subsystems. POLAR has a cylindrical shape with a 2.8 m diameter base and 1.25 m in height (plus 1.25 m more for the despun platforms), it has solar cells to provide power, weights 1 250 Kg and uses 333 W of power. The spin rate of the satellite is 10 RPM around and axis almost normal to the orbital plane. It also has long wire spin-plane antennas, spin-plane appendages to support the sensors and internal booms. The satellite has 2 despun gimbaled instrument platforms, and in the Z axes the booms are deployed.

The data is stored in tape recorders on-board and sometimes relayed to the Deep Space network at a maximum speed of 600 kbps and 41.6 kbps in average.
magnetosphere.

1.2 Ground Station

Our ground station will be a small city called Bondy in France, our observer location is :

1. Longitude : 2.478680
2. Latitude : 48.89976

Figure 1.2: Ground stations

Our ground station is located approximately 800 km away from Bremen.

Chapter 2

Tracking our satellite

In order to obtain the subpoints of the satellite, we could either use the emphem module or the following formulas :
Latitude φ :

$$\varphi = \arcsin[\sin(i) \cdot \sin(\nu + \omega)]$$

Longitude λ :

$$\lambda = \arctan[\tan(\omega + \nu) \cdot \cos(i)] - \left[\frac{\Omega_E}{n}(E - e \cdot \sin(E) - \frac{\Omega_E}{n} \cdot (E_N - e \cdot \sin(E_n)) \right]$$

For simplicity reasons, we will use the built-in functions for both the subpoints and the computing of elevation, distance and azimuth with respect to the observer. Those are obtained by the PyEphem package which takes the TLE of the satellite and the ground station longitude and latitude as arguments. The code used is in the Jupyter Notebook.

We can then plot the ground track of the POLAR satellite over 5 days starting on 20^{th} December 2019 :

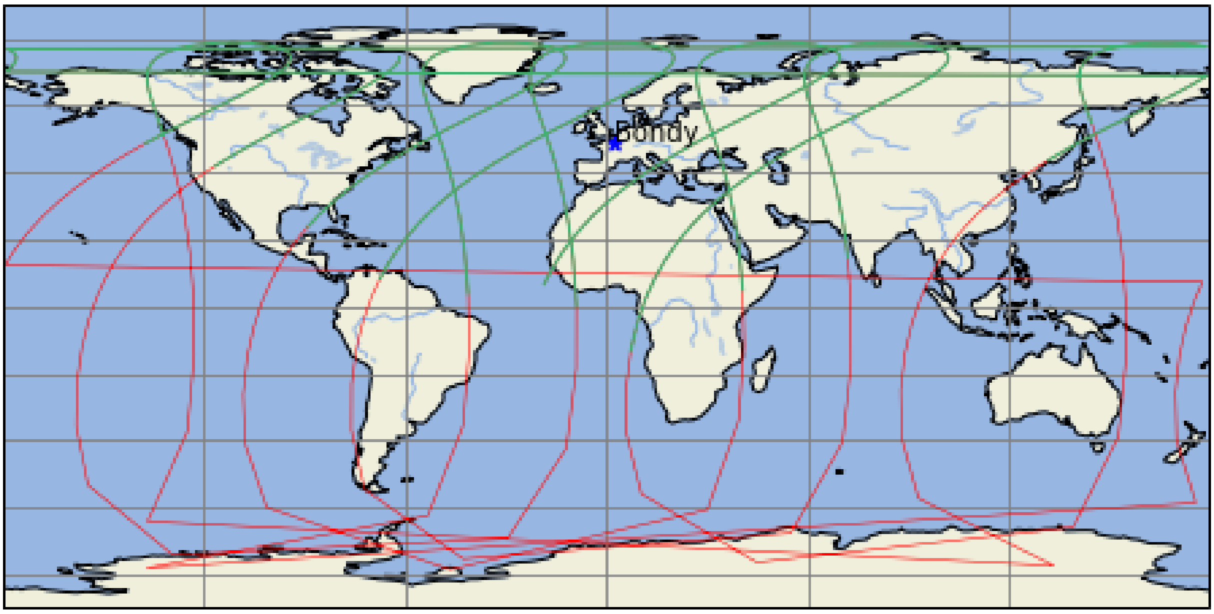

Figure 2.1: Ground track of POLAR satellite

The red plot is the actual ground track of the satellite and the ground track becomes green when the satellite becomes visible to the ground station. Our visibility condition is that the elevation is at least 5°.

We can then plot the elevation, the distance and the azimuth of the satellite with respect to the ground station over the observation days. Those are also obtained by using the respective PyEphem built-in functions *alt*, *range* and *az*. For the elevation, the green area is the part in which the satellite is visible to our observer in accordance to the minimal elevation angle.

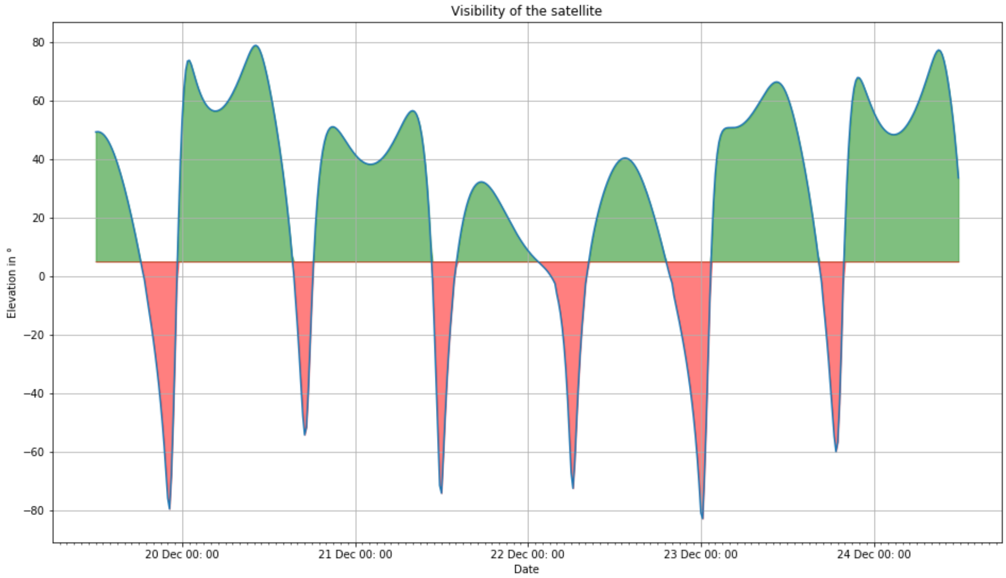

Figure 2.2: Elevation of POLAR satellite with regard to the ground station

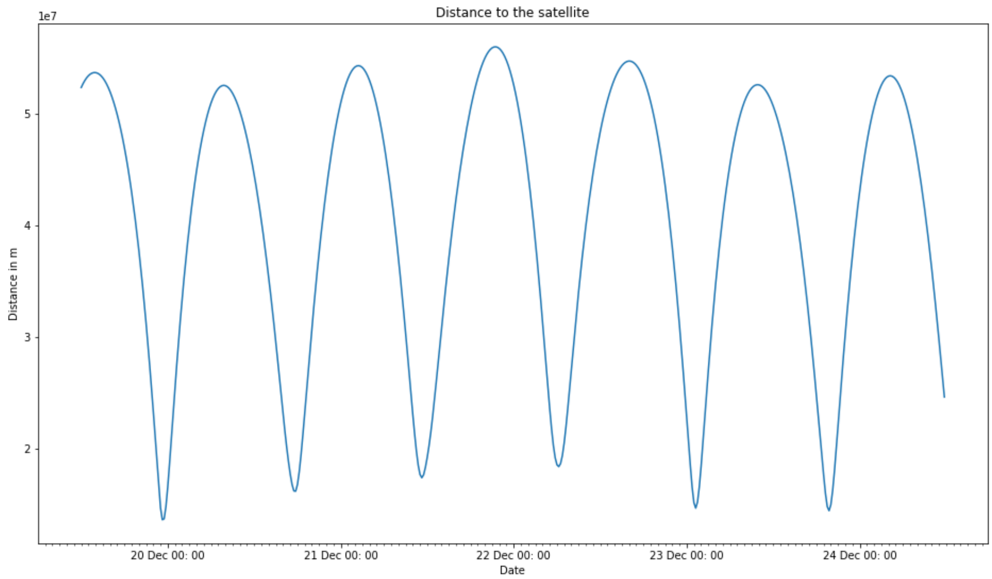

Figure 2.3: Distance of POLAR satellite from the ground station

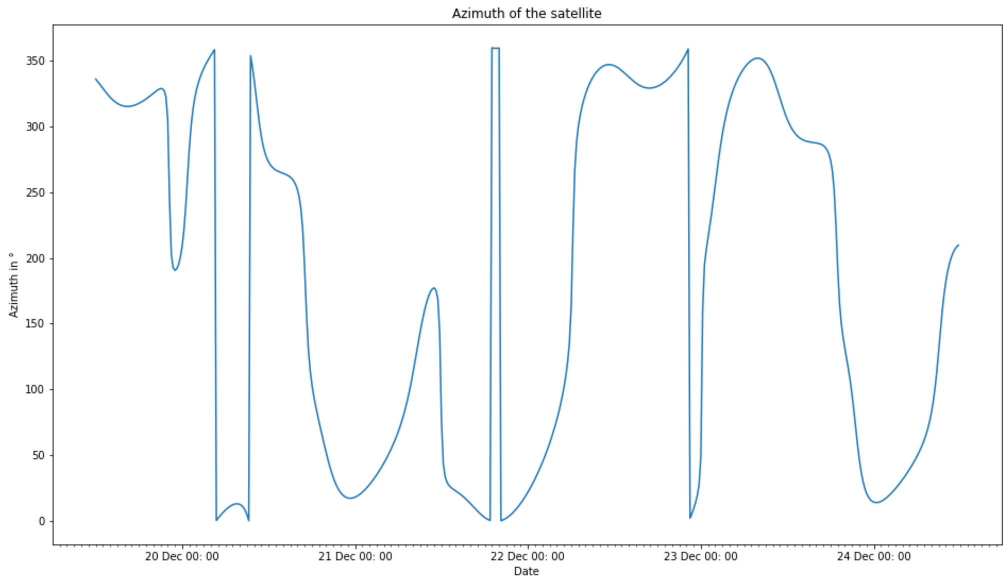

Figure 2.4: Azimuth of POLAR satellite with regard to the ground station

This elevation graph is in accordance with the visible slots on the ground track. When it comes to the distance, it is mainly oscillating between 1×10^7 m and 5.6×10^7 m.

The azimuth might look weird at first but it makes sense as the our satellite has a polar orbit with high inclination which then creates such unperiodic function. Moreover, we should keep in mind that those jumps are caused by the fact that the angles are brought back to a 360° basis.

2.1 Connection windows

2.1.1 Largest window

As we got the information of the orbit of our satellite and its "behavior" with regards to our ground station, we need to find the connection windows we have and make sure that our satellite have the necessary conditions to send us data. The communication windows during our observed timespan are the following :

1. Start of window = 2019/12/20 00:00:00
   End of window = 2019/12/20
   06:00:00 Duration = 06:00:00

2. Start of window = 2019/12/20 11:30:00
   End of window = 2019/12/21 03:15:00
   Duration = 15:45:00

3. Start of window = 2019/12/21 06:15:00
   End of window = 2019/12/21 22:30:00
   Duration = 16:15:00

4. Start of window = 2019/12/22 02:15:00
   End of window = 2019/12/22 13:15:00
   Duration = 11:00:00

5. Start of window = 2019/12/22 20:30:00
   End of window = 2019/12/23 07:00:00
   Duration = 10:30:00

6. Start of window = 2019/12/23 13:30:00
   End of window = 2019/12/24 04:15:00
   Duration = 14:45:00

Those windows have been calculated with a large margin as our time resolution was 15 minutes. We then choose to focus on the largest window which is the 3^{rd} one with a duration of approximately 58 500 s.

2.1.2 Ground track on the largest window

We can then plot the ground track of our satellite during that specific window :

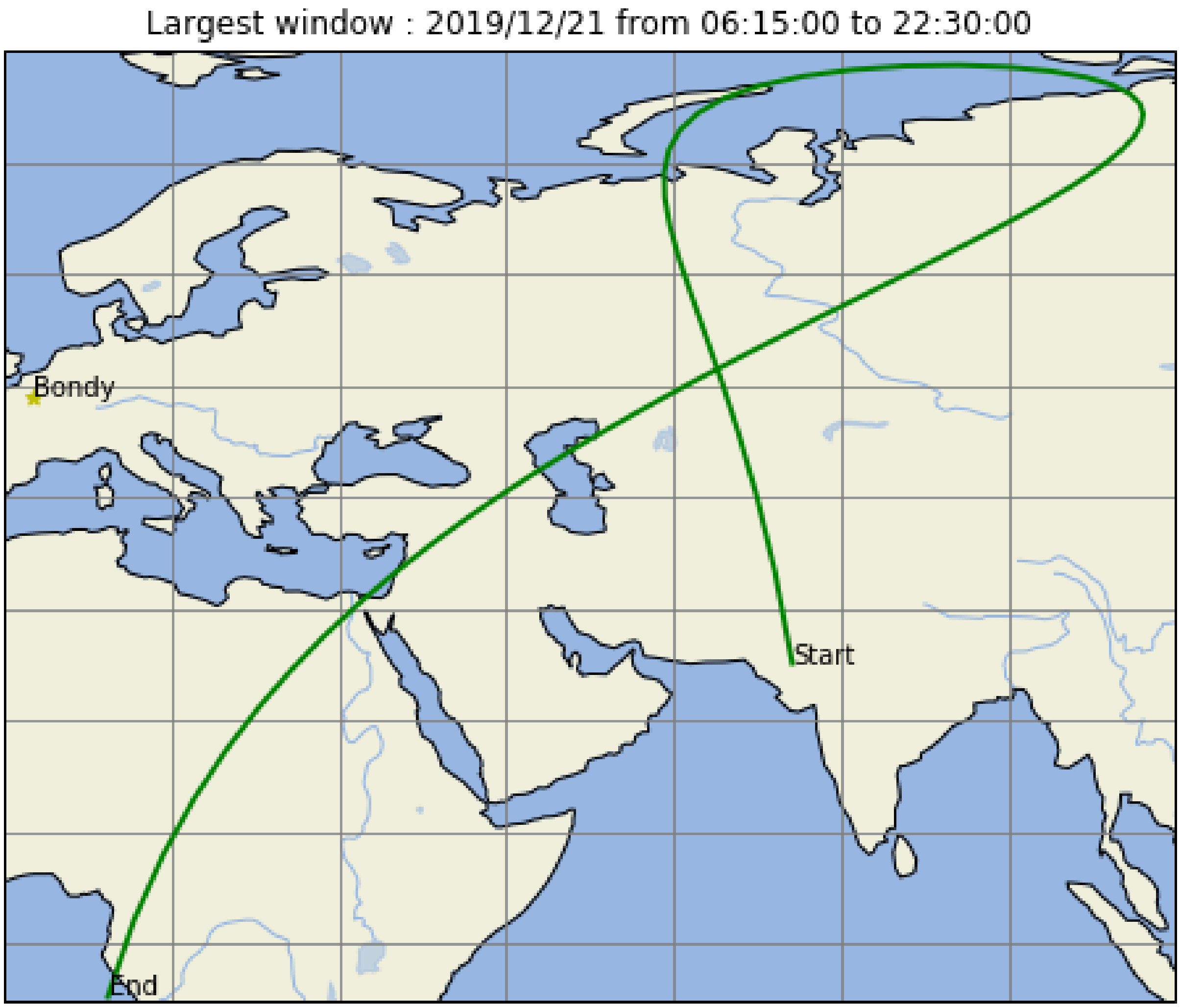

Figure 2.5: Ground track during the largest window

2.1.3 Distance, azimuth and Doppler shift on the largest window

We can also take a closer look at the distance from the ground station, the elevation, the azimuth and the Doppler shift on that window :

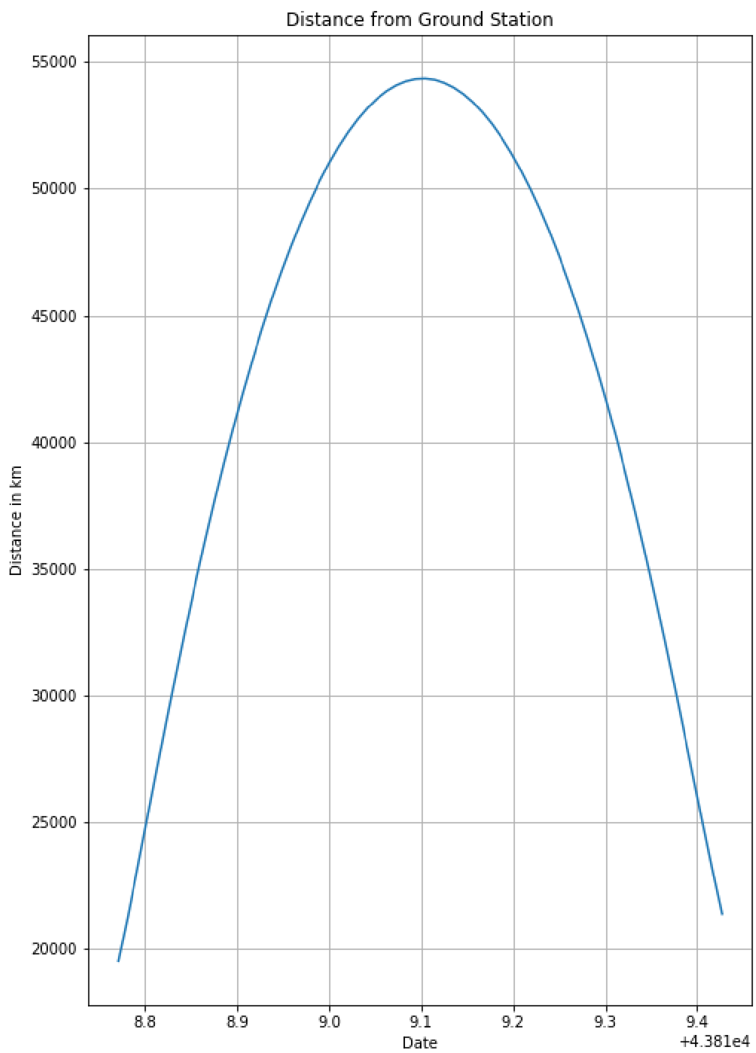

Figure 2.6: Distance during the largest window

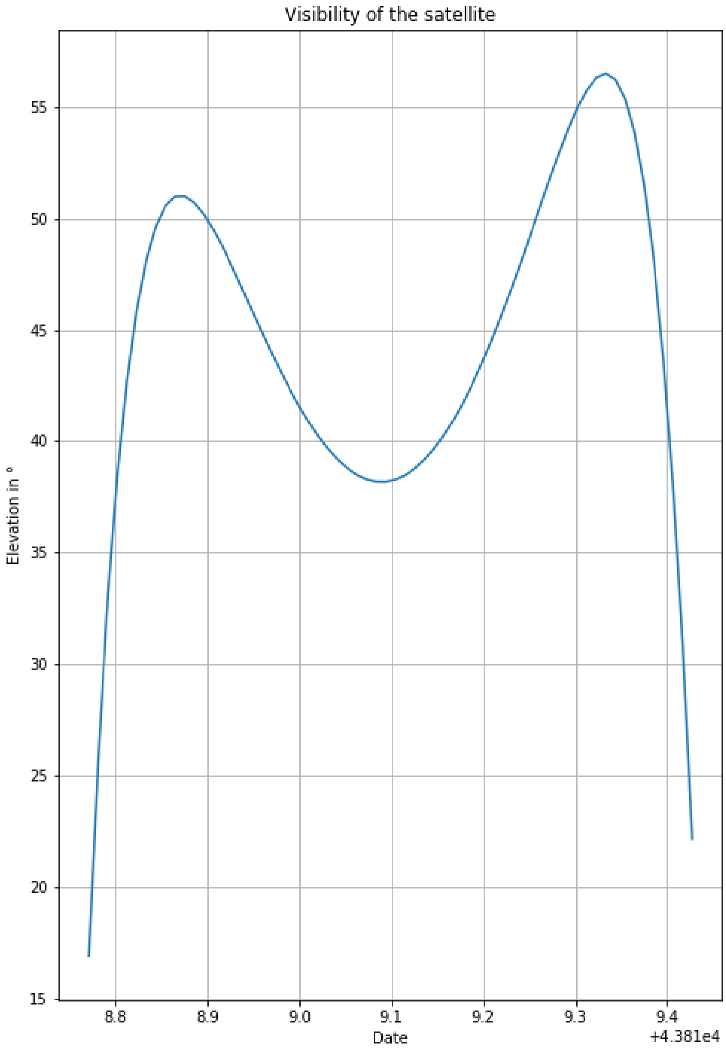

Figure 2.7: Elevation during the largest window

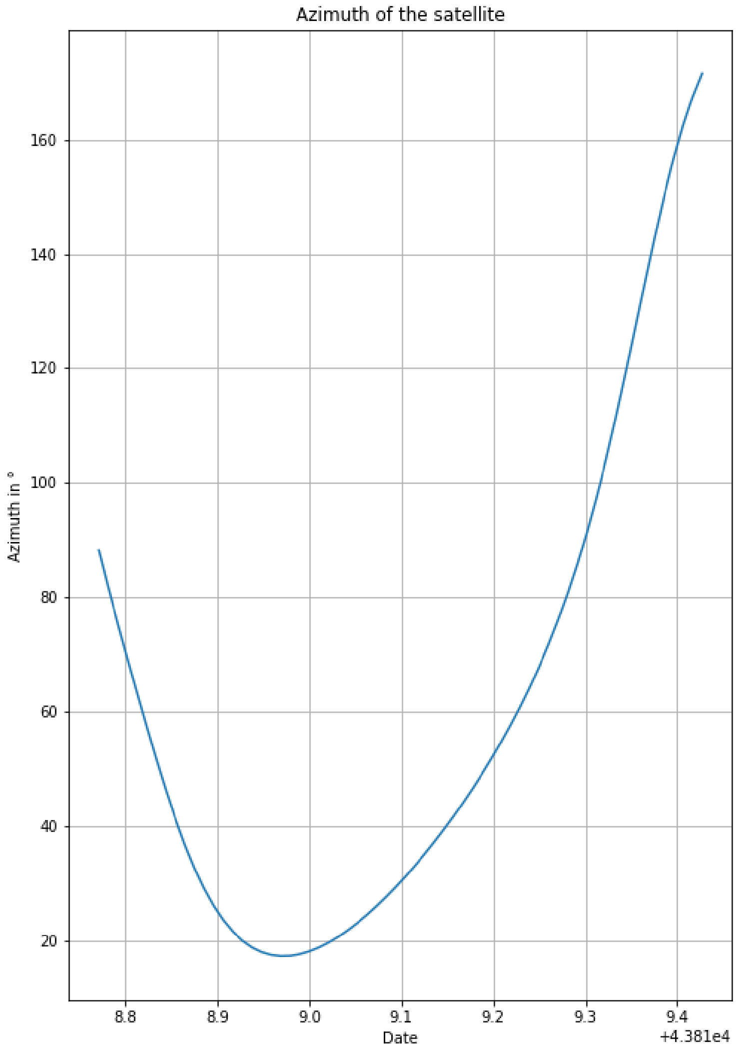

Figure 2.8: Azimuth during the largest window

Doppler shift

The Doppler shift can be obtained by :

$$\Delta_f = \frac{f v_r}{c}$$

With :

- f the frequency of the signal : 8345 MHz in our case
- v_r the range velocity obtained via PyEphem
- c the speed of light in vacuum 3×10^8 m/s

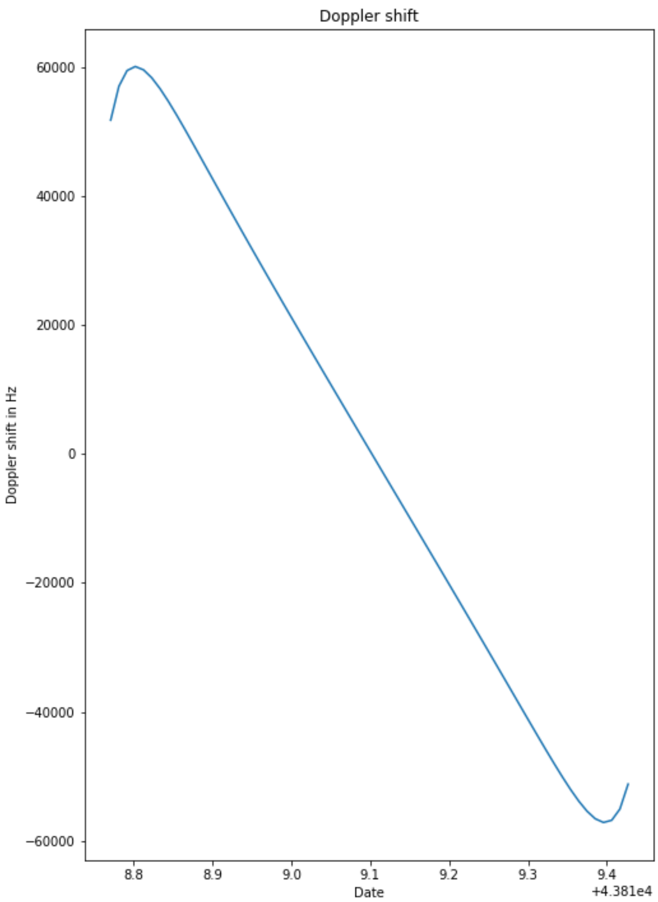

Figure 2.9: Doppler shift during the largest window

Chapter 3

Link and Power budgets

3.1 Link Budget

3.1.1 Data bit rate and symbol rate

For the transmission, QPSK (quadrature phase shift keying) modulation is used. The modulation has 4 states so $M = 4$ and m can be calculated as $\log_2 M = 2$.

For 16.25 hours of connection time, the required data bit rate R_c and symbol rate R_a can be obtained by the following expressions:

$$R_c = \frac{\#\ of Bits}{T_{con}} = \frac{1000\,\mathrm{MByte} \cdot 8 \cdot 10^8}{58500\,\mathrm{s}} = 136752.14\,\mathrm{bit/s} \tag{3.1}$$

$$R_a = \frac{R_c}{m} = \frac{136752.14\,\mathrm{Bit/s}}{2} = 68376.07\,\mathrm{symbol/s} \tag{3.2}$$

3.1.2 Required Bandwidth

To calculate the bandwidth we will use the following expression:

$$B = \frac{R_c}{\Gamma} \tag{3.3}$$

We need the value of the roll-off factor which is $\alpha = 0.15$ to calculate the spectral efficiency Γ:

$$\Gamma = \frac{m}{1+\alpha} = \frac{2}{1+0.15} = 1.74 \tag{3.4}$$

And therefore, going back to the equation 3.3 the bandwidth value is:

$$B = \frac{136752.14}{1.74} = 7.86 \cdot 10^{-4}\,\mathrm{Hz} \tag{3.5}$$

3.1.3 Required SNR

For the required BER of 10^{-6} and a QPSK modulation scheme, we will use the graph in Figure 3.1 to obtain the Energy per bit per noise ratio $\left(\frac{E_c}{N_o}\right)$ and we get a value of $\frac{E_c}{N_o} \approx 10.5\,\mathrm{dB}$

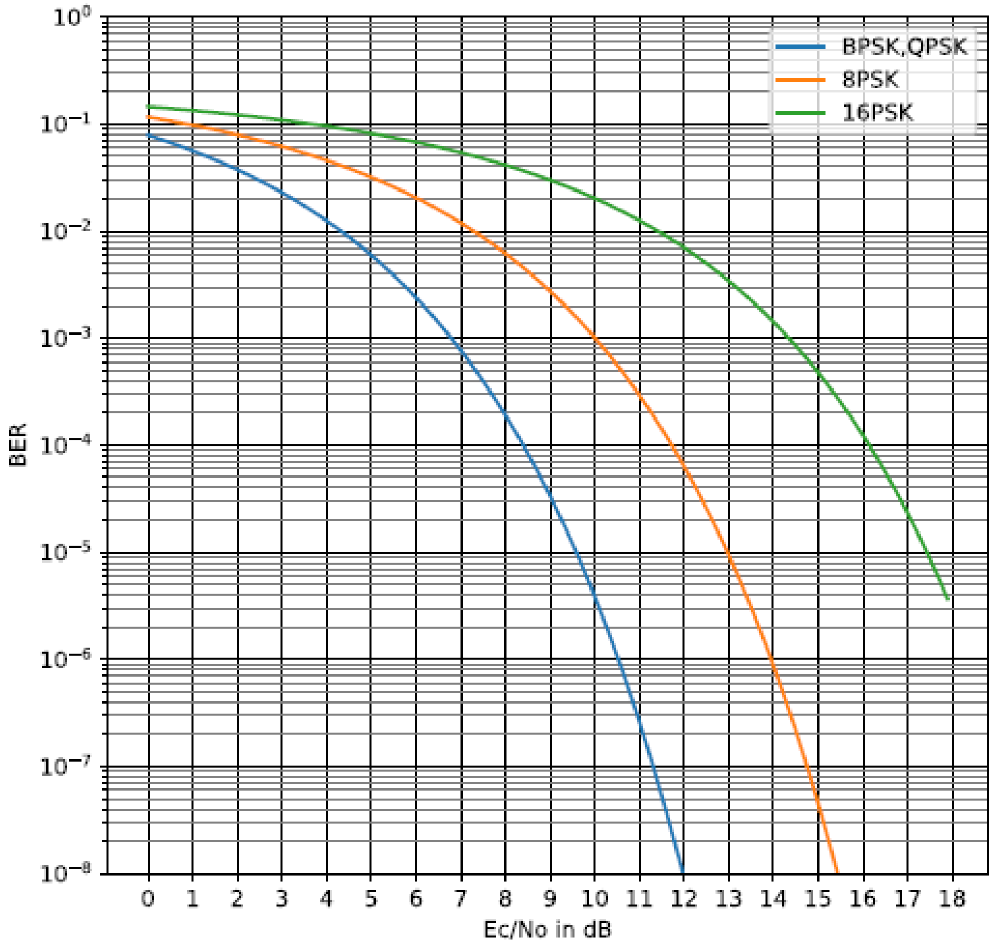

Figure 3.1: Bit Error Ratios for different Modulation Schemes

Once we have the $\frac{E_c}{N_o}$ we can proceed to calculate the SNR:

$$SNR = \frac{R_c \cdot \frac{E_c}{N_o}}{B} = \frac{136752.14 \cdot 10.5}{7.86 \cdot 10^{-4}} = 19,51 \tag{3.6}$$

3.1.4 Receiver and noise

To calculate the total received noise at the antenna of the ground station N_i we can use the following expression:

$$N_i = k \cdot T_a \cdot B \tag{3.7}$$

In which the k is the Bolzmann constant with a value of $1.38 \cdot 10^{-23}\,\mathrm{J/K}$, B is the previously calculated bandwidth and T_a is the antenna noise temperature, which can be found in the graph of Figure **??**.

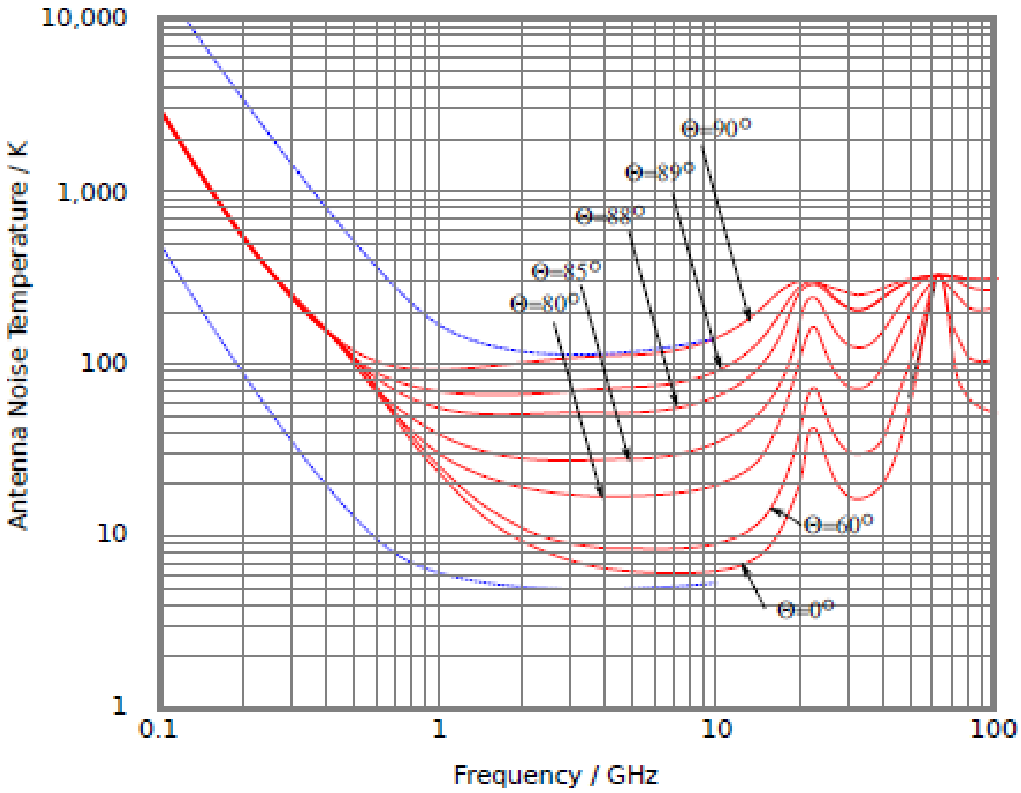

Figure 3.2: Antenna noise temperature T_a as a function of the Zenith angle and the frequency.

To calculate the T_a we will take the worst case scenario under consideration, which is for an elevation of 5° (Zenith Angle $\Theta = 85°$). In this case we get a $T_a \approx 30.5\,\mathrm{K}$

Now that we have calculated all the values we can put them back in Equation 3.7:

$$N_i = 1.38 \cdot 10^{-23} \cdot 30.5 \cdot 7.86 \cdot 10^{-4} = 4.21 \cdot 10^{-17}\,\mathrm{W} \tag{3.8}$$

To obtain the input noise N_o we will use the following calculation:

$$N_o = k \cdot (T_a + Te) \cdot B \cdot G_r \tag{3.9}$$

In which k is the the Bolzmann constant, T_a is the previously calculated antenna noise temperature, T_e is the equivalent noise temperature, B is the Bandwidth and G_r is the gain of the receiver in the ground station.

To calculate the equivalent noise temperature T_e we need the noise figure, which is given as $F = 2\,\mathrm{dB}$ and the initial temperature T_0 which is set at 290 K:

$$T_e = (F - 1) \cdot T_0 = 169.62\,\mathrm{K} \tag{3.10}$$

With all the parameters from Equation 3.9 known, besides the gain of the receiver in the ground station which is set to a design value of $G_r = 100000$, we can calculate the N_o:

$$N_o = 1.38 \cdot 10^{-23} \cdot (30.5 + 169.62) \cdot 7.86 \cdot 10^4 \cdot 100000 = 2.76 \cdot 10^{-11}\,\mathrm{W} \tag{3.11}$$

3.1.5 Required signal powers

To calculate the required signal power S_o we use the following equation:

$$S_o = SNR \cdot N_0 = 19,51 \cdot 2.76 \cdot 10^{-11} = 5,39 \cdot 10^{-10}\,\mathrm{W} \tag{3.12}$$

And to obtain the input signal power S_i we will use the receiver gain that we assume before to be 100000 W (or 60 dB):

$$S_i = \frac{S_0}{G_r} = \frac{5,39 \cdot 10^{-10}}{100000} = 5,39 \cdot 10^{-15}\,\mathrm{W} \tag{3.13}$$

3.1.6 Required EIRP in worst case scenario

To calculate the EIRP for the worst case scenario with an elevation of 5° we can use the following formula:

$$\begin{gathered} EIRP = SNR{\cdot}L_p \cdot k \cdot B \cdot \frac{T_a + T_e}{G_a} = \\ 19.51 \cdot 3.84 \cdot 10^{20} \cdot 1.38 \cdot 10^{-23}{\cdot}100000 \cdot \frac{30.5 + 169.61}{4.39 \cdot 10^3} = 451.31\,\mathrm{W} \end{gathered} \tag{3.14}$$

3.1.7 Design a transmitter with 30% efficiency and a matching dish antenna

Finally we ought to design a transmitter with a 30% efficiency and its antenna. For the transmitter we set a design value of 25 W. The first thing we have to calculate is the gain of the transmitter G_t:

$$G_t = \frac{EIRP}{P_t} = \frac{451.31}{25} = 18.05 \tag{3.15}$$

Now that we have the gain of the transmitter, we will proceed to define the size of the antenna. For knowing its diameter D, we will have to know the phisical area of the antenna A_{phy}, and for that the effective area of the antenna A_{eff}:

$$A_{eff} = \frac{G_t \cdot \lambda^2}{4 \cdot \pi} \tag{3.16}$$

Where lambda λ is the wavelenght and can be calculated with the frequency f and the speed of light c:

$$\lambda = \frac{c}{f} = \frac{2.998 \cdot 10^8}{8.35 \cdot 10^9} = 3.59 \cdot 10^{-2}\,\mathrm{m} \tag{3.17}$$

Going back to the Equation 3.16:

$$A_{eff} = \frac{18.05 \cdot (3.59 \cdot 10^{-2})^2}{4 \cdot \pi} = 1.86 \cdot 10^{-3}\,\mathrm{m}^2 \tag{3.18}$$

$$A_{phy} = \frac{A_{eff}}{\eta_t} = \frac{1.86 \cdot 10^{-3}}{0.3} = 6.18 \cdot 10^{-3}\,\mathrm{m}^2 \tag{3.19}$$

$$D = 2 \cdot \sqrt{\frac{A_{phy}}{\pi}} = 2 \cdot \sqrt{\frac{6.18 \cdot 10^{-3}}{\pi}} = 8.87\,\mathrm{m} \tag{3.20}$$

3.2 Summary table

Description	Quantity	Value	Unit
Frequency	f	$8,35 * 10^9$	Hz
Tx-Power	Pt	25	W
Tx-Antenna gain	Gt	18.1	
Tx-EIRP	EIRP	$4.51 * 10^2$	W
Tx Dish Diameter	D	$8.87 * 10^{-2}$	m
Mod. Scheme	QPSK		
Bandwidth	B	$7.86 * 10^4$	Hz
Max. Distance to Ground	r	$5.60 * 10^7$	m
Rx-Antenna Gain	Gr	10^5	
Rx-Dish Diameter	D	1	m
G/T of Rx	G/T	22.9	K^{-1}
Received Power	Prec	$5.39 * 10^{-15}$	W

3.3 Power Budget

3.3.1 Battery capacity and solar cell area

To calculate the battery capacity we will need the power consumption P_{tot} and the time that the satellite is in the shadow $t_{eclipse} = 3hours$. For the power we have assumed that the platform requires 500 W when it is in the sun and 100 W when it is in the shadow.

$$CB = \frac{P_{tot}}{t_{eclipse}} = \frac{P_{psun} + P_{pshadow} + P_t}{t_{eclipse}} = \frac{500 + 100 + 25}{3} = 208.33\,\mathrm{Wh} \tag{3.21}$$

For the required solar cell area A_{sol} we will need the Irradiance M_{sol} which has a value of $1367\,\mathrm{W/m^2}$, the efficiency of the cell η_{cell} which we set to 0.15 and the power required by the satellite when it is in the sun P_{sol}.

To calculate the P_{sol}(Equation 3.23) we need to know first the power that it consumes to charge the battery $P_{charging}$, for which we need the period of the elipse T_{elipse}, the time on the shadow $t_{eclipse}$ and the efficiency of the battery η_{bat}, as well as the already calculated battery capacity CB.

$$P_{charging} = \frac{CB}{\frac{T_{elipse} - t_{eclipse}}{\eta bat}} = \frac{208.33}{\frac{18.5 - 3}{0.8}} = 16.80\,\mathrm{W} \tag{3.22}$$

$$P_{sol} = P_{charging} + P_{psun} + P_t = 16.80 + 500 + 25 = 541.80\,\mathrm{W} \tag{3.23}$$

Now that we have all the values we can calculate the required solar cell area A_{sol}:

$$A_{sol} = \frac{P_{sol}}{M_{sol} \cdot \eta_{cell}} = \frac{541.80}{1367 \cdot 0.15} = 2.64\,\mathrm{m^2} \tag{3.24}$$

List of Figures