Satellite Communications

Satellite system to provide communication services to polar regions in Europe and Russia

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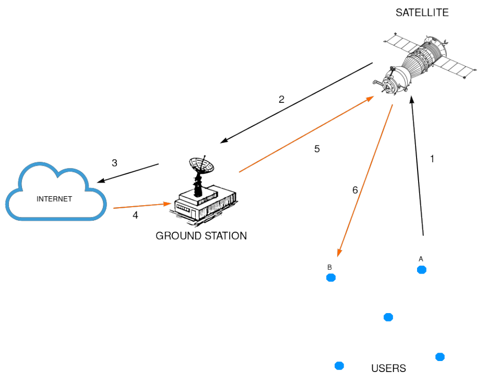


Figure 1: Scheme of the topology of the system.

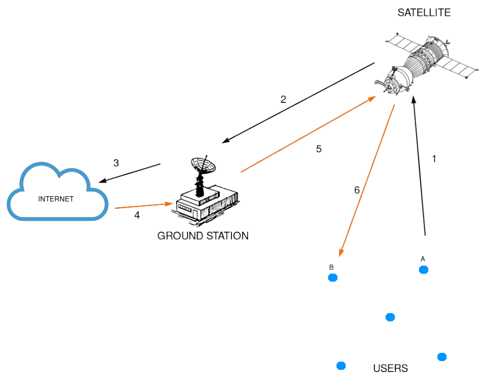


Figure 2: Typical communication path between an user A and an user B.

1. Problem Description

This project results from the necessity of having a good broadband coverage of polar areas and the land areas of Northern Europe and Russia: this means the coverage of latitudes over 60°.

The subjects interested in this kind of communication are mostly industries involved in economic sector: they need a reliable communication system able to provide a service of 50 Mbps in download and 5 Mbps in upload.

The aim is to project a system able to provide a continuous, reliable and feasible communication service, maximizing the number of users allowed to access it over 60° latitudes and minimizing the costs. To do that, services in narrowband communication using LEO satellites are not useful, since the broadband communication required is not feasible with this technology.

A simple representation of the system to be built is shown in Figure 1 and a communication between two users is in Figure 2.

Typically, if a user A has to communicate with user B, it sends his packets to the satellite, with the recipient address in the header. The satellite receives the packets and forwards them to the Ground Station that sends them to the proper application (Skype, Hangout, ...). These packets are sent from the application to the Ground Station, that forwards them, through the satellite, to the recipient B.

2. Simulator and Orbits

To guarantee the service required in section 1., different orbits have been taken in account. The most used orbit to ensure a stable and reliable satellite communication is Geostationary. Figure 3 has been taken from the Inmarsat's Website, and it shows as a Geostationary Earth Orbit (GEO) satellite can not reach the latitudes over 75°. For this reason a GEO does not fit our purpose.

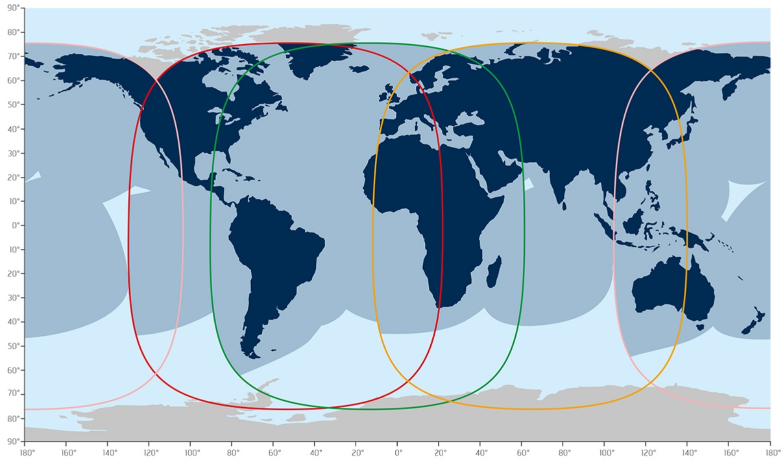


Figure 3: Approximate coverage of GEO Satellites.

Low Earth Orbits (LEOs) has been discarded since the time of visibility for a single satellite is very low, so an high number of satellites and an accurate tracking system are required to ensure a continuous service.

Medium Earth Orbits (MEOs) suffer the same problems of LEO ones, with the addition of the proximity to the Van Allen Belt where signal degradation increases significantly.

The most suitable solution for our problem is an High Elliptical Orbit (HEO), in particular we chose to analyse *Tundra* and *Molniya* orbits.

To analyse the behavior of these orbits, an orbital simulator has been implemented using MATLAB. The simulator architecture and its results are reported in subsection 2.1.

2.1 Simulator Architecture

Our simulator is organized in a main file and several other files that serves as functions for the main one. In the follows a brief explanation of each part of the script is presented. For the sake of simplicity, a one-satellite simulator is taken in account, the extension to a multi-satellite model is explained later. The main file is organized in different sections where external functions are called:

- Initialization of all the fixed parameters used inthe simulation;
- computation of the trajectory of a satellite in thechosen orbit in terms of Orbital Coordinates system;
- Earth Centered Inertial (ECI) and geodetic latitude, longitude, altitude coordinates (LLA) coordinates are computed;
- plot of a 3D animation in which the satellite and its trajectory are shown;
- plot of the Ground Track of the satellite;

- estimation of azimuth and elevation of the satellite viewed from the Ground Station (GS) position;
- link budget estimation.

In case of more than one satellite, each one has to cover the same area of the Earth but in different moments, and since the Earth rotates, a simple delay in the same orbital plane is not enough.

The solution we found for this problem is a delay in the time (with the same trajectory) and a different Right Ascending of Ascension Node (RAAN) for each satellite. The RAAN's offset angle of each satellite is given by the orbital period (T) of the orbit. *Tundra* is a Geosynchronous Orbit, so its orbital period is the same of the Earth, and the following formulas have been used:

$$d^{time}(s) = \frac{T}{n} \qquad d^{raan}(deg) = \frac{360}{n} \tag{2.1}$$

Where T is the orbital period and n is the number of satellites simulated.

In case of a *Molniya* orbit, the orbital period is an half the revolution period of the Earth, so the RAAN has to be an half of the one calculated for *Tundra*. In formulas:

$$d^{time}(s) = \frac{T}{n} \qquad d^{raan}(deg) = \frac{360}{2n} = \frac{180}{n} \tag{2.2}$$

With a multi-satellite system, the GS has to communicate each time with the best satellite, i.e. the satellite with the higher elevation. Based on this assumption, the best satellite in each instant is calculated in the script and the actual elevation and azimuth of the GS's antenna is plotted.

Finally, the Overall Link Budget for a GS in each instant is the one calculated between the GS itself and the best satellite in that moment.

2.2 Orbit selection

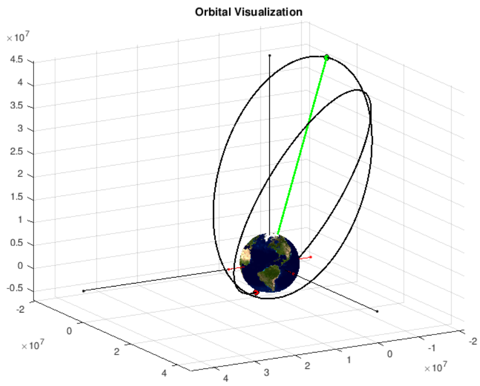
The parameters of the orbits analysed in the simulator are presented in Table 1.

	Tundra	Molniya
Orbital Period (s)	86400	43200
Eccentricity	0.25	0.71
Semi-major axis (km)	42164	26556
Inclination (deg)	63.4	63.4
Initial RAAN (deg)	120	25

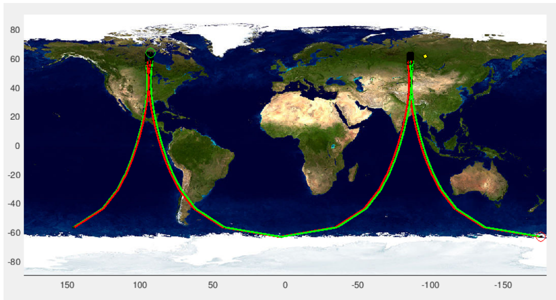
Table 1: Parameters of the considerated orbits

In the simulation, two satellite equally spaced are used: when the first is in the apogee, the other is in the perigee. As is shown in Figure 4 and Figure 5, each satellite has its own orbital plane, but the ground track for the different satellite is the same. In specific, the RAAN's offset between satellites is 90° for Molniya and 180° for Tundra.

Since Molniya's period is an half of the revolution period of the Earth, two revolutions of the satellites around the Earth have been simulated, to make the understanding of the figures easier. In case of Tundra, one revolution around the Earth is enough since this orbit is Geosynchronous.



(a) 3D Visualization



(b) Ground Track

Figure 4: Graphical visualization of Molniya orbit

Plotting the azimuth and the elevation for different position in the service area (Figure 6), the result is that the elevation with a Molniya Orbit is, on average, higher. In same cases, the advantage of Molniya is not so visible from the elevation plots, but calculating the Link Budget, it gives higher values for Molniya than for Tundra.

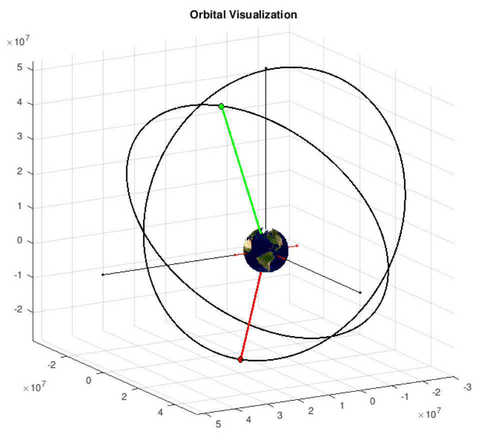
For all these reasons, we chose to adopt a Molniya orbit with the parameters set as in Table 1 for our system.

3. Payload and Space Segment

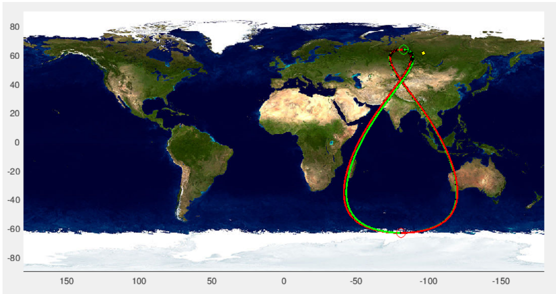
For the space segment a payload a considerations on the transponders have been made based on the requirements that the mission has to satisfy: to be precise, the problem description requires a broadcast communication that guarantees a capacity of 5 Mbit in uplink and of 50 Mbit in downlink; moreover the communication has to allow the internet connection and video and voice call service.

3.1 Communication Module

The first thing to do was to select the transponder size, which we fixed at 72 MHz. After that we decided the number of carriers in for the forward and the return link and the



(a) 3D Visualization



(b) Ground Track

Figure 5: Graphical visualization of Tundra orbit

amplitude of the guard-band between the carriers. The resulting values are listed in Table 2 and Figure 7 shows a schematic representation of a transponder.

Through these values the total number of transponder we have on the satellite is 12, 6 with horizontal polarization and 6 with the vertical one.

3.2 Frequency Plan

After these considerations the structure of the Frequency Plan is automatically elaborated and here it is represented in Figure 8

Feature	Value
Transponder size	72 MHz
N carriers in forward link	2
N carriers in return link	6
Amplitude carriers in fw	27.805 MHz
Amplitude carriers in rt	2,732 MHz
Tot. fw link bandiwdth	55.61 MHz
Tot. rt link bandwidth	16.39 MHz
Guard-band	3.6 MHz
Tot. bandwidth used	450 MHz

Table 2: Values for the communication module

3.3 Payload

The electronic part of the payload is composed by the two main sections of the **receiver block** and **repeater block**: in the first part, the signal is received, separated in polarization, filtered and amplified so as to be ready for the repeater part, in which it is channelized and further amplified. Figure 9 shows the global representation of the payload.

3.3.1 Receiver Block

The main actions in which this block is involved are the **polarization separation** and the **frequency conversion**; Figure 10 shows accurately all the fundamental components of this first part.

- (1) is the polarization diplexer, which has the role of separating the received signal depending of its polarization; Figure 10 only shows the path for one possible polarization, but in the complete payload scheme all the components that follow the diplexer have to be doubled up;
- (2) is a low noise amplifier necessary for a first recovering of the received signal; this amplifier is the main element which determines the figure of merit G/T of the transponder and thus it must have a low noise temperature (in this case is estimated of 438,45 K with a noise figure of 4 dB) and a high gain (in this case of 30 dB) in order to limit the role of the noise of subsequent stages.
- (3) is the frequency oscillator: its values change with respect to the frequency we need to convert, as shown in Table 3. For the oscillator we have to monitor also other parameters like the conversion losses (normally in the order of 5 - 10 dB, we supposed the worst case of 10 dB and so a noise temperature of 2610 K) and the stability of the frequency [1];
- (4) is the High Power Amplifier necessary to amplify the converted signal before being channelized in the repeater section;
- we also have to consider the role of the cables and the losses they bring inside the estimations; in our case we supposed a loss due to the cables of about 3 dB and an associate noise temperature of 288.63 K.

For this block the redundancy is of 1/2.

3.3.2 Repeater Block

In the repeater block the channelization part is present and, for that, the input/output multiplexers are needed. We selected 2 input and 2 output multiplexers, each one having 3 channels in order to have one channel per carrier received[1]. Inside the multiplexers

[1]we remember that the path described here is still referring to one single polarization. At the end of the description, all the elements described have to be doubled up in number

Downlink frequency	Oscillator frequency
$10.95 \leq f_d \leq 11.2$ GHz	1.5 GHz
$11.54 \leq f_d \leq 11.7$ GHz	2.58 GHz
$12.5 \leq f_d \leq 12.75$ GHz	3.8 GHz

Table 3: Oscillator frequency values depending of the Downlink frequency needed for an uplink frequency between 14 and 14.5 GHz

the main elements are the band-pass filters and the circulators used to separate the frequency channels, these ones are the main cause of losses inside the multiplexers since they depend on the number of times the signal concerned passes through a circulator (the loss is in the order of 0.1 dB).

In addition to this, for each channel of the multiplexers we then have:

- (8), a channel amplifier;
- (9), an Automatic Level Control module: a device needed to guarantee a constant power value as input of (10);
- (10), the amplifier module, composed by the EPS and the TWT sections which together form the Travelling Wave Tube Amplifier (TWTA). The output power value that we supposed for the TWTA section is 20W [1].

For this block the redundancy is a 8/12 redundancy ring.

3.4 Power Budget

The power budget mainly depends on the power required by the TWTA amplifiers in order to transmit the signal to the Earth. As can be seen from the chart in Figure 12, the fraction of power that the communication subsystem requires is about 75 %, all the other utilities uniformly share the remaining power needed.

3.4.1 Required Power

To estimate the required power we supposed to be in the worst case (end of life of the satellite) and followed the steps below:

- Estimate the End Of Life (EOL) efficiency for the solar panel;
- Estimate the EOL efficiency for the TWTA module;
- Estimate the EOL efficiency for the EPC module;
- Estimate the total power required for the transponders;
- Estimate the total power required for the system;

Solar panel efficiency Given an expected life of 15 years, a degrading coefficient $\frac{1}{\tau}$ of 0.043 1/s and an initial efficiency of 17 %, the EOL solar panel efficiency is:

$$\eta_{SP_{EOL}} = \eta_{BOL} e^{-0.043T} \rightarrow \eta_{SP_{EOL}} = \frac{17}{100} e^{-0.043 \times 15} = 8.9\% \tag{3.3}$$

TWT efficiency The same expression can be used to estimate the EOL efficiency for the TWTA, supposing a $\eta_{TW_{BOL}} = 60\%$: in particular, if we suppose that the efficiency value will be reduced of 10% after 10 years (6% of decrement), we can find the degradation coefficient $\frac{1}{\tau}$ as:

$$60\% - 6\% = 60\% e^{\frac{-10}{\tau}} \rightarrow \tau = \frac{-10}{log_e \frac{54}{60}} = 94.91 \quad s^{-1} \tag{3.4}$$

and so the EOL efficiency:

$$\eta_{TW_{EOL}} = 60 e^{\frac{-15}{94.91}} = 51.23\% \tag{3.5}$$

EPC efficiency Through the same procedure we obtain also the efficiency for the EPC segment:

$$\eta_{EPC_{EOL}} = 81.2\% \tag{3.6}$$

Total power required for the transponders With all the efficiency values previously found we can now estimate the total power used by the satellite in the worst case, supposing an output power at saturation for the TWT module of 250 W:

$$P_{in_{TW}} = \frac{P_{out_{TW}}}{\eta_{TW_{EOL}}} = 195.198 \text{ W} \tag{3.7}$$

$$P_{in_{EPC}} = \frac{P_{in_{TW}}}{\eta_{EPC_{EOL}}} = 240.39 \text{ W} \tag{3.8}$$

$$P_{transp} = P_{in_{EPC}} \times N_{transp} = 240.39 \times 12 = 2.885 \text{ kW} \tag{3.9}$$

$$\tag{3.10}$$

Moreover, since this power consists in the 75% of the total power necessary for the satellite, the total power for the satellite is:

$$P_{tot} = \frac{P_{transp}}{75\%} = 3.846 \text{ kW} \tag{3.11}$$

3.4.2 Solar Panels specifications

Once we have found the total power that the satellite needs at the worst case, the estimation of the area for the solar panels is made deploying the following expression:

$$A_{panel} = \frac{P_{tot} s}{f \Phi \eta_{SP_{EOL}} s(1-l)} \tag{3.12}$$

Where:

- s is the area of a single cell;
- Φ is the solar flux, supposed to be of 1215,74 W/m^2 in the farthest point of the satellite orbit (based on the observation of Figure 13);
- f is the filling efficiency, here of the order of 90 %;
- l are general losses due to cabling and cover and typical values are 10 to 15 % (here we selected 15 % for a worst-case analysis);

And from it the final value for the solar panel area of our satellite is:

$$A = 46.46\ m^2 \tag{3.13}$$

3.5 Weight Estimation

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4. Ground Segment

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Parameter	Value
Frequency Band	Ku Band
Dish diameter D	6 m
Efficiency	0.6
IBO	-0.5 **(Cri says: può essere considerato un parametro d'antenna?)**

Table 4: GS antenna specifications

4.1 Ground Station coordinates

The coordinates of the GS are: **(Cri says: Cambia valore quando Davide ha trovato un buon posto per la GS)**

$$lat = 61.267865 \tag{4.14}$$
$$long = -96.608223 \tag{4.15}$$
$$\tag{4.16}$$

These coordinates have been chosen based on the elevation values: the coordinates listed above represent a point in Russia in the surrounding area of the subsatellite point of the apogee. In this way, the values of elevation are always substantially high, guaranteeing always a good visibility. Moreover, another factor is the rain attenuation, which is not much high in this region, as we can conclude from the respective value of R: **(Cri says: Cambia valore quando Davide ha trovato un buon posto per la GS)**

$$R = 22.2016 \quad mm/h \tag{4.17}$$

4.2 Ground Station requirements

The requirements for the GS are substantially the following:

- the Internet connection;
- the antenna model and specifications.

The Internet connection is the most important (if not the only one) reason for the existence of the GS, since one of the problem requirements is indeed the possibility of video calls and other internet services.

For the antenna model we chose a reflector antenna with a single circular beam; the antenna parameters are listed in Table 4

(Cri says: la metto sta frase qui? a suo tempo il prof mi pare avesse detto che andava specificato, però a leggerla mi rattristo a pensare che offriamo un servizio che per 2 minuti al giorno sistematicamente non funziona)

4.3 User requirements

The user requirements are substantially the model of the antenna and the dimension of the dish: the model is identical to the ones used for the satellite and the GS, so a reflector antenna with a single beam; the dish diameter is smaller in this case, for a matter of space and feasibility, and is of 1 m **(Cri says: verifica valore)**. There is no need, in this case, of specifying the position of the users since by definition they are mobile users.

5. Link Budget

In this section, the Link Budget for the Forward Path is computed.

In the first part, the parameters used in the calculation are presented and discussed, then is calculated the Link Budget for the Uplink (GS to Satellite), the Downlink (Satellite to the user) and the overall one.

5.1 Parameters setting and estimation

5.1.1 Antenna Parameters

To compute the link budget we need the parameters of Satellite, Ground Station and User antennas. These are taken from [2] and reported in Table 5.

	Symbol	Value
GS antenna diameter (m)	d_{GS}	6
Sat antenna diameter (m)	d_{SAT}	1.2
Sat antenna noise temperature (K)	t_A^{SAT}	290
User antenna diameter (m)	d_{US}	1
User antenna noise temperature (K)	t_A^{US}	80
Antennas Efficiency	η	0.6

Table 5: Antennas parameters used in the Link Budget calculation

t_A^{SAT} is set to $290K$ since satellite receiver antenna *sees* the full thermal radiation of the Earth, t_A^{US} is set to $80K$ since typical values for a Ku-Band receiver antenna in the Downlink are between $60K$ and $80K$, and $80K$ is the value that most decrease the Link Budget. All the antenna's efficiencies are set to 0.6, since typical values are between 0.6 and 0.75, so the worst case has been taken.

Knowing the diameter of the antenna reflector, its efficiency and the wavelength of the communication, the gain of each antenna can be computed as in Equation 5.18.

$$g = \eta \left(\frac{\pi d}{\lambda} \right)^2 \qquad G = 10log\left[\eta \left(\frac{\pi d}{\lambda} \right)^2 \right] \; dBi \tag{5.18}$$

The result for each antenna are in Table 6.

	Symbol	Value
GS antenna gain (dB)	G_{GS}^{TX}	56.92
Sat antenna gain while receiving (dB)	G_{SAT}^{RX}	42.94
Sat antenna gain while transmitting (dB)	G_{SAT}^{TX}	40.68
User antenna gain (dB)	G_{US}^{RX}	39.1

Table 6: Gain of each antenna in transmission and reception

5.1.2 Losses

The losses due to noise and attenuation in the payload and some to atmospheric conditions are constant and are reported in Table 7. All the attenuations are in dB.

	Symbol	Value
Input Backoff	IBO	-16
Output Backoff	OBO	-10.47
Losses due to multicarrier operation	l_{mc}	10.47
Losses due to feeder	l_{ftx}	0.5
Carrier to interference noise	C/I	23
Pointing Loss	l_p	0.3
Gases absorption	l_{gas}	0.3

Table 7: Constant losses

Losses due to rain L_{rain} and the Path Loss L_{pl} depends on the position of the satellite and on the carrier frequency.

For the GS we calculated a rain intensity $R = 11.4919\ mm/h$, we assumed that the rain is 2km high and calculating the rain attenuation as in Equation 5.19 we obtain the plots in Figure 14 and Figure 15.

$$L_{rain} = kR^{\alpha}L_s r_p \tag{5.19}$$

The parameters in Equation 5.19 are calculated as in Equation 5.20.

$$\begin{aligned} k &= 4.21 \times 10^{-5} \cdot f^{2.42} \\ \alpha &= 1.41 \cdot f^{-0-0779} \\ L_s &= \frac{2km}{sin\theta} \\ r_p &= \frac{90}{90 + 4L_s cos\theta} \end{aligned} \tag{5.20}$$

where f is the carrier frequency in Uplink or in Downlink and θ is the elevation angle.

The path loss also depends on the position of the satellite and is calculated with the formula in Equation 5.21, where r is the distance between the satellite and the GS or the user, taking in account the altitude of the latter, and λ is the wavelength of the communication.

$$L_{PL} = 20log\left(\frac{2\pi r}{\lambda}\right)\ dB \tag{5.21}$$

Using Equation 5.21 in each istant of the simulation, we obtain the plots in Figure 16 and Figure 17.

5.1.3 Effective Isotropic Radiated Power(EIRP)

To calculate Effective Isotropic Radiated Power (EIRP) we have to compute firstly the power that each antenna has to transmit p_{tx}. The power that each transponder has to transmit is calculated as in Equation 5.22, using the parameters yet defined, than this power has to be multiplied for the number of transponder in the system, that in our case is 12, the final formula is in

$$p_{tx}^{1T} = [p_{HPA}]_{dB} - l_{mc} - l_{ftx} \tag{5.22}$$

$$p_{tx} = p_{tx}^{1T} + 10log(12) \tag{5.23}$$

Then the EIRP is calculated for Uplink and Downlink with the formula in Equation 5.24.

$$EIRP = G_{tx} + p_{tx} \tag{5.24}$$

For the Uplink, using G_{GS}^{TX} as gain, the result is $EIRP_{GS} = 96.79\ dB$, while for the Downlink, using G_{SAT}^{TX} as gain, the result is $EIRP_{SAT} = 66.58\ dB$.

5.2 Uplink

5.3 Downlink

5.4 Overall Link Budget

6. Cost Estimation

6.1 Spacecraft cost

The spacecraft cost can be estimated depending on several parameters and criteria, such as the type of mission, the subsystem considered and the unit over which calculate the cost. In our specific case we concentrated on the cost analysis for a communication-type satellite and review it for every subsystem of the spacecraft and its launch procedure.

The subsystems analyzed are the following:

- Attitude determination and Control subsystem (ADCS)
- Communication subsystem

Subsystem	Mean Cost (k€)	Standard deviation
IA&T	8311,49	8719,94
EPS	8441,34	5681,80
Structure	4111,49	2955,92
SEPM	12167,05	7825,63
Thermal	903,45	562,3
TT&C	4423,24	2942,24

Table 8: List of the costs per subsystem

- Electrical power subsystem (EPS)
- Integration assembly and test (IA&T)
- Passive sensor
- Propulsion
- System engineering
- Structure
- Thermal control
- Telemetry tracking and command (TT&C)

In particular, Figure 18 shows the cost percentage that each system represents: from it we can see that the System engineering is the most important item, followed by the EPS and the IA&T subsystems. Moreover, Figure 19 lists the different sections, depending on the type of mission the satellite is intended to accomplish, with their standard deviations; tables 20 and 21, instead, show the total cost depending on the mission type and the total cost per pound.

Regarding the cost per subsystem, Table 8 and Table 9 show the different cost each subsystem is intended to have:

Through this data we can make a raw hypothesis on the average total cost of the spacecraft with a summary estimation of its mass:

6.2 Launch cost

For the launch cost we based our considerations on the prices listed by the *SpaceX* company. Figure 22 shows the prices for different types of launches, depending on the mass of the spacecrafts and the orbits they should reach.

Through the considerations we have made in the previous sections we can state that around 180 Millions of dollars (151.793.055 €**(Cri says: verifica il prezzo)**) are needed for the launch: in fact each spacecraft has a total mass of about **(Cri says: mettere**

Subsystem	Mean Cost/unit (k€/kg or ch)	Standard deviation
ADCS	94,70	8719,94
Communication ($1 < ch < 10$)	3923,19	1443,98
Communication ($10 < ch < 25$)	1534,45	558,37
Communication ($25 < ch$)	708,40	197,35
EPS	24,7	7,27
Propulsion	54,68	14,32
Structure	15,94	4,37

Table 9: List of the costs per subsystem per pound/channel

Communication spacecraft		
IA&T	8311,49 €	+
EPS	24,7 €/Kg	$\times NCHILI+$
Structure	15,94 €/Kg	$\times NCHILI+$
SEPM	12167,05 €	+
Thermal	903,45 €	+
TT&C	4423,24 €	+
ADCS	94,70 €/Kg	$\times NCHILI+$
Propulsion	54,68 €/Kg	$\times NCHILI+$
Communication ($10 < ch < 25$)	1534,45 €/ch	$\times 12ch =$
Total cost:		TOT

Table 10: List of the costs per subsystem per pound/channel

massa) and the Molniya orbit is a HEO orbit; moreover, since the raans of the two orbital planes are separated of 180 deg it is necessary to use two separate launchers, one for each spacecraft.

Through this analysis the total cost for the project is:

$$Cost_{Total} = Cost_{Launch} + Cost_{Spacecraft} = \textbf{(Cri says: Mettere costo finale)}€ \tag{6.25}$$

7. Final considerations and conclusions

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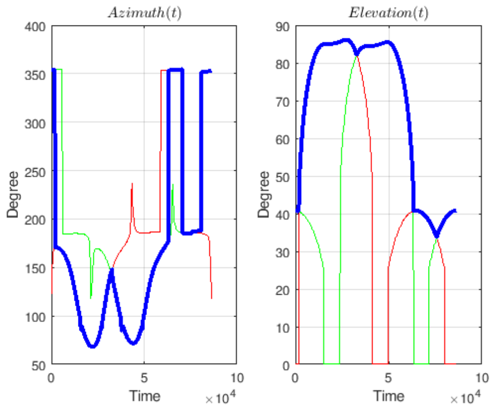
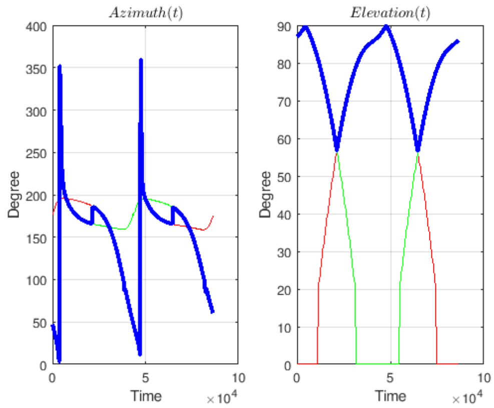
References

[1] B. M. Maral Gérard, *Satellite communications systems. Systems, techniques and technologies.* Wiley, 2009.

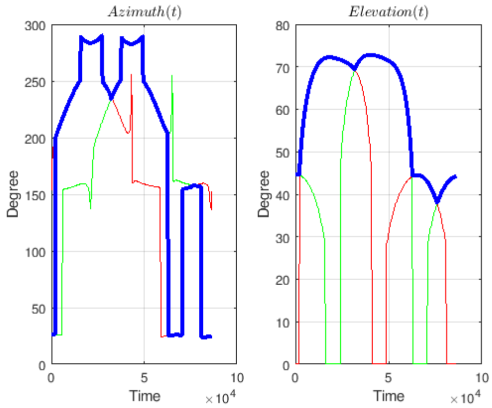
[2] L. J. Ippolito, *Satellite Communications Systems Engineering Atmospheric Effects, Satellite Link Design and System Performance.* Wiley, 2017.



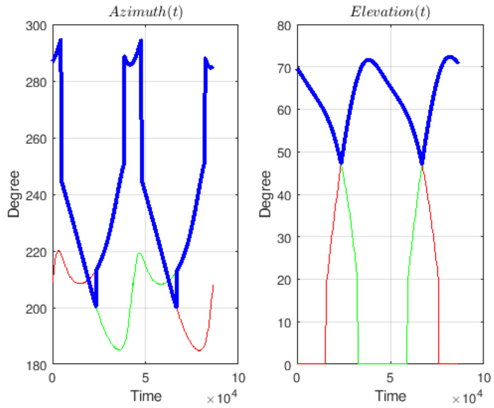
(a) Molniya, $Lat = 61°$ $Long = -75°$



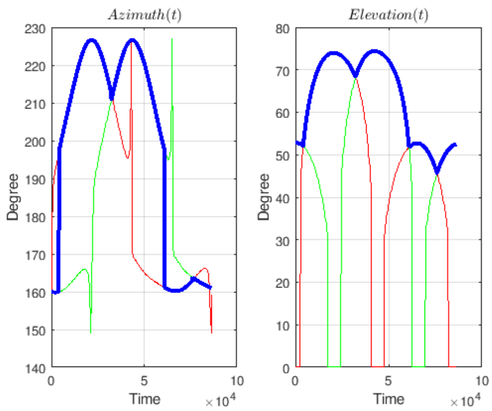
(b) Tundra, $Lat = 61°$ $Long = -75°$



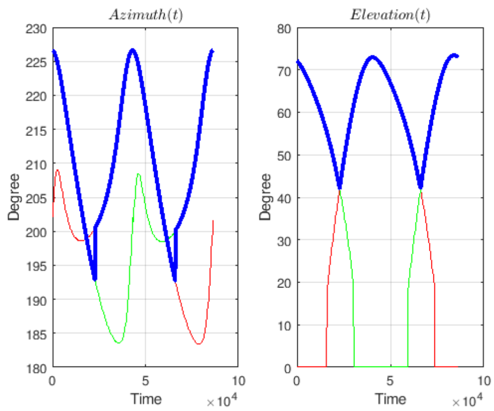
(c) Molniya, $Lat = 61°$ $Long = -130°$



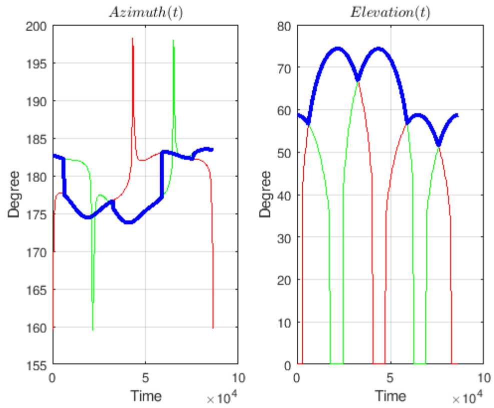
(d) Tundra, $Lat = 61°$ $Long = -130°$



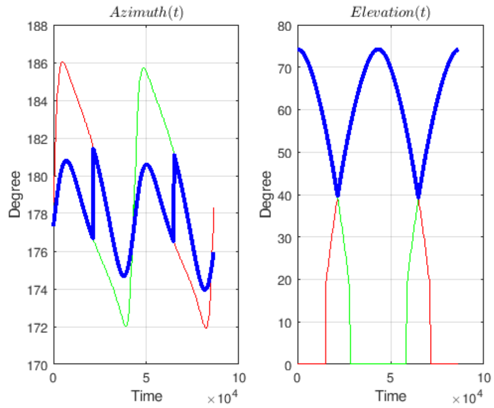
(e) Molniya, $Lat = 71°$ $Long = -130°$



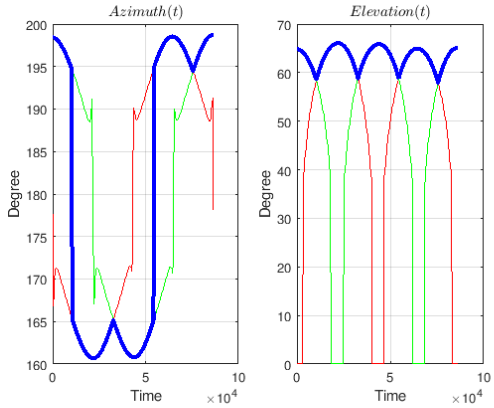
(f) Tundra, $Lat = 71°$ $Long = -130°$



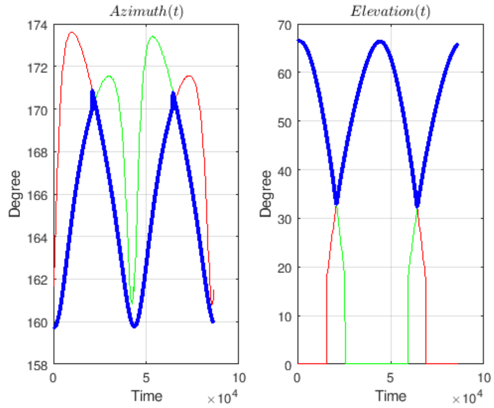
(g) Molniya, $Lat = 81°$ $Long = -75°$



(h) Tundra, $Lat = 81°$ $Long = -75°$



(i) Molniya, $Lat = 81°$ $Long = 0°$



(j) Tundra, $Lat = 81°$ $Long = 0°$

Figure 6: Elevation and Azimuth for different position in the service area of Molniya and Tundra orbits

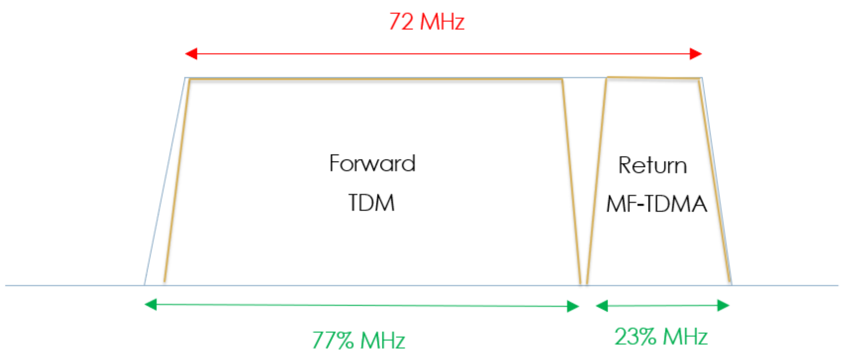


Figure 7: Representation of a transponder

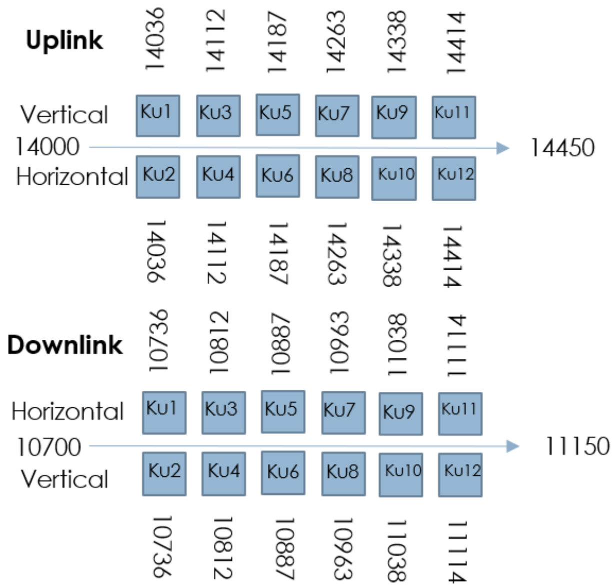


Figure 8: Frequency plan for the communication module

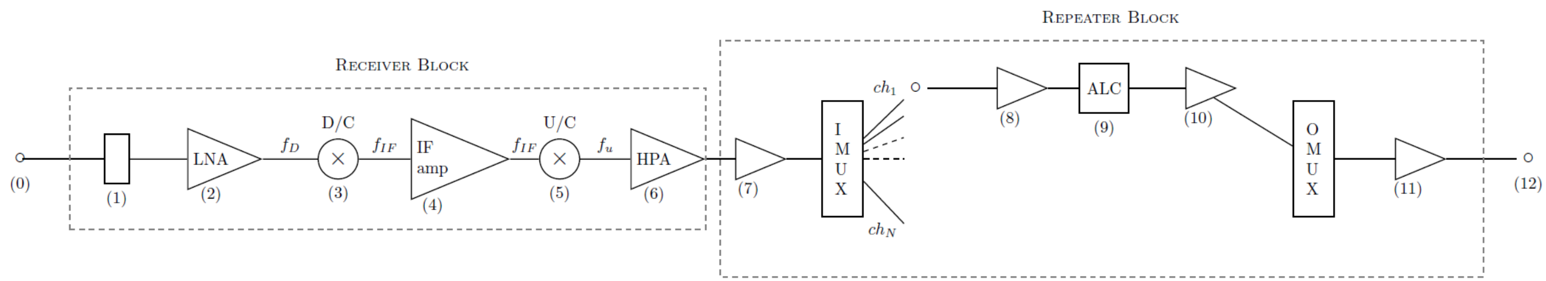


Figure 9: Payload representation

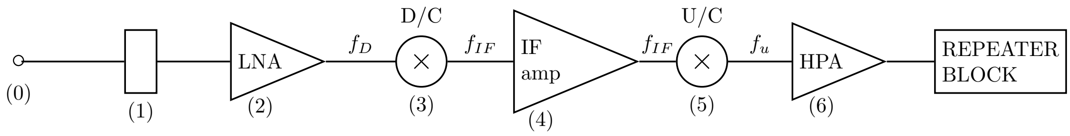


Figure 10: Payload receiver part

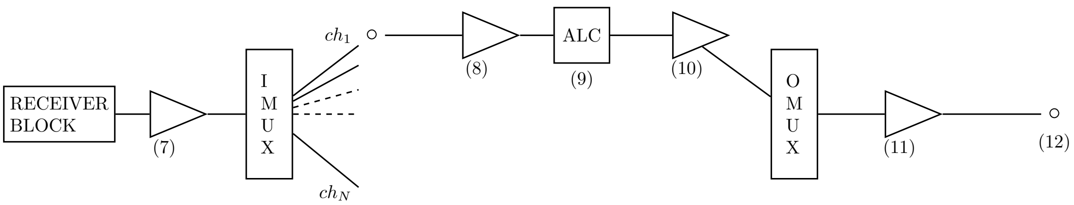


Figure 11: Payload repeater part

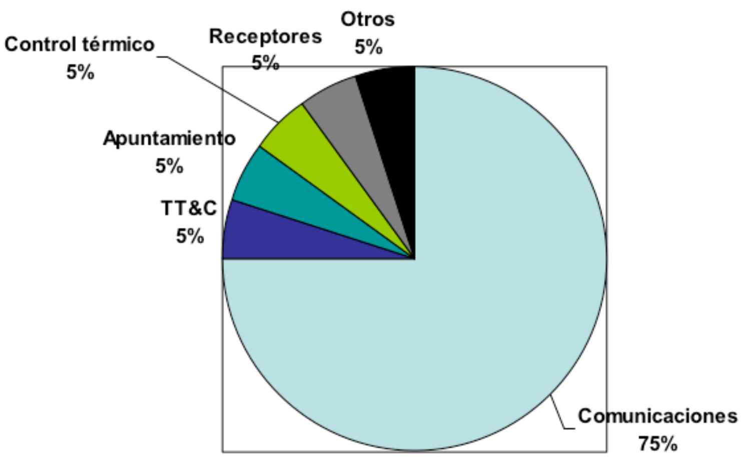


Figure 12: Power distribution among the subsystems in percentage

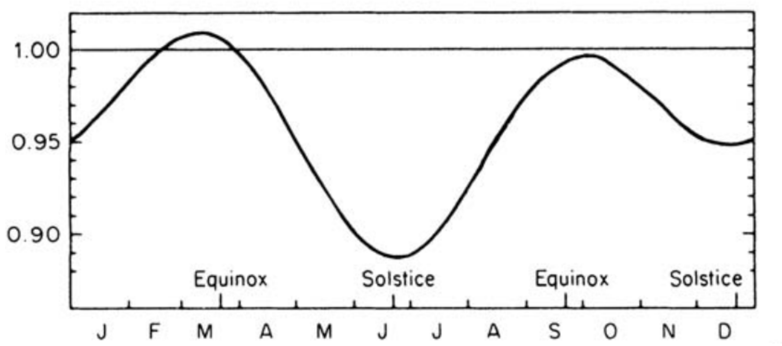


Figure 13: Combined influence of sun declination and distance variation

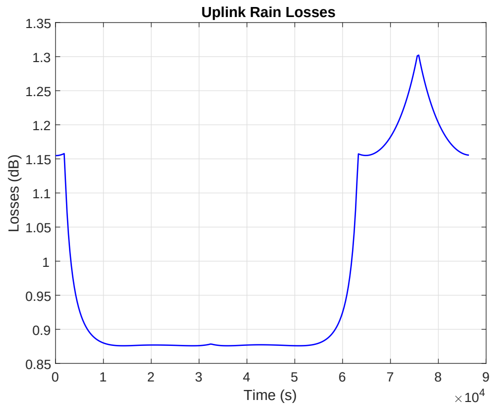


Figure 14: Variation of rain losses in Uplink over the time

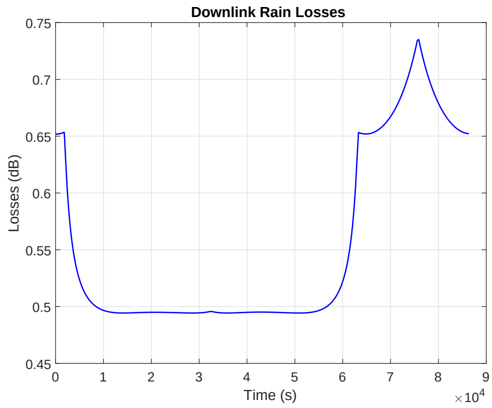


Figure 15: Variation of rain losses in Downlink over the time

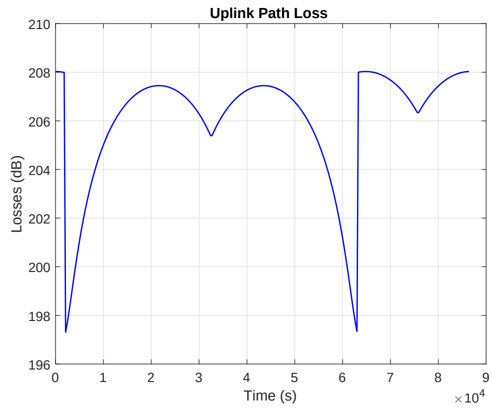


Figure 16: Variation of Path Loss in Uplink over the time

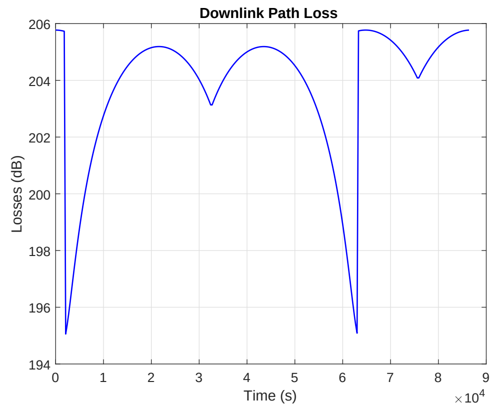


Figure 17: Variation of Path Loss in Downlink over the time

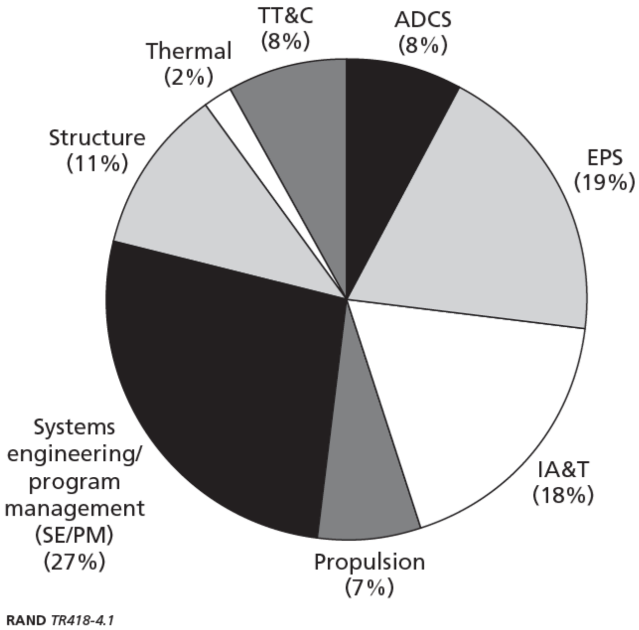


Figure 18: Communication spacecraft cost composition

Cost	Average (%) (standard deviation)							
	ADCS	EPS	IA&T	Prop	SE/PM	Structural	Thermal	TT&C
Communication	8.0 (2.2)	19.1 (7.9)	18.0 (8.6)	6.6 (3.3)	26.8 (9.2)	11.2 (6.7)	2.3 (1.4)	8.0 (3.5)
Environmental	19.8 (6.1)	15.6 (4.2)	15.6 (9.0)	4.1 (1.9)	24.9 (6.8)	5.4 (2.4)	1.4 (0.7)	13.2 (4.3)
Navigation	13.6 (2.4)	21.0 (3.2)	16.9 (4.2)	7.7 (1.5)	20.0 (7.9)	7.6 (5.4)	3.1 (0.3)	10.1 (3.6)
Scientific/survey	11.4 (1.4)	12.3 (7.8)	22.2 (13.0)	3.6 (4.5)	25.0 (8.8)	8.2 (3.7)	1.9 (0.9)	15.4 (18.2)
Experimental	9.6 (4.8)	12.0 (2.2)	13.9 (4.6)	8.0 (9.3)	23.3 (7.3)	10.0 (5.5)	1.4 (2.6)	22.0 (4.5)
Communication/ navigation/ environmental	12.0 (6.4)	18.3 (6.8)	17.2 (8.2)	6.0 (3.0)	25.5 (8.5)	9.2 (6.1)	2.1 (1.2)	9.8 (4.3)

Figure 19: Communication spacecraft cost composition: averages and standard deviations

Spacecraft T1 by Mission ($K)

Mission	# Obs	Mean	Std Dev
Communications	17	31,214.76	9,587.34
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	30.7	17,875.95	50,273.65

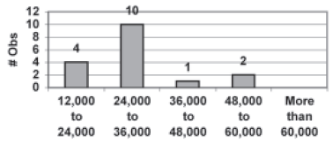


Figure 20: Total spacecraft cost

Mission	# Obs	Mean	Std Dev
Communications	17	15.56	6.63
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	42.6	8.05	26.61

Communications SC weigh between 1200.7 and 3857.3 lbs

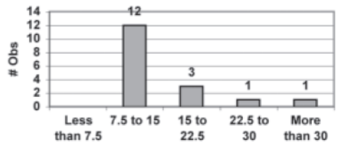


Figure 21: Total spacecraft cost per pound

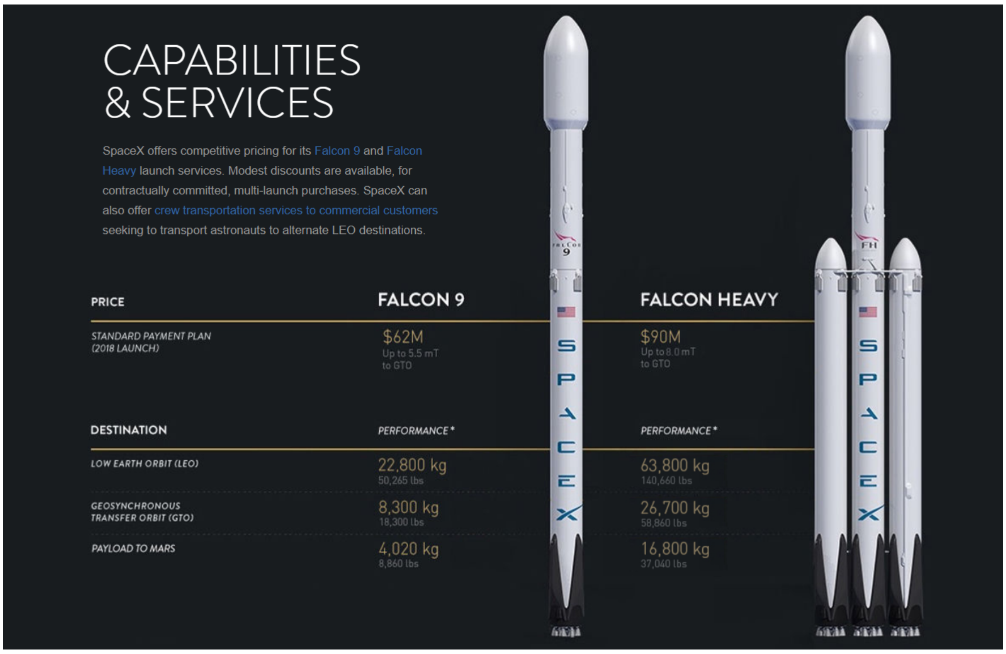


Figure 22: *SpaceX* price list