Satellite Communications

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

Ana Reviejo Jiménez
Marta Munilla Díez
Oscar Pla Terrada
Davide Peron
Cristina Gava
Javier Garcia Camin

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Contents

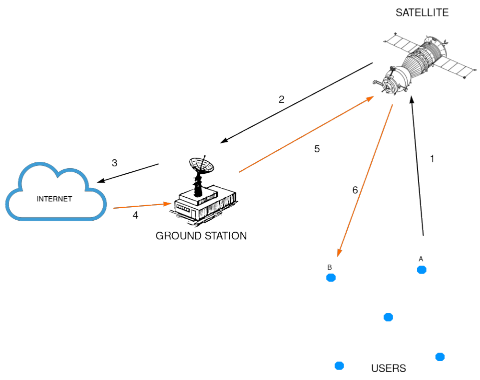


Figure 1: Scheme of the topology of the system.

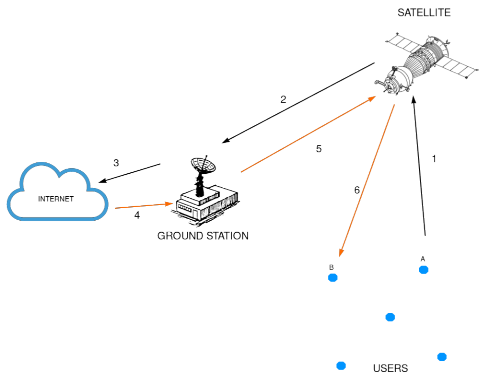


Figure 2: Typical communication path between an user A and an user B.

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.

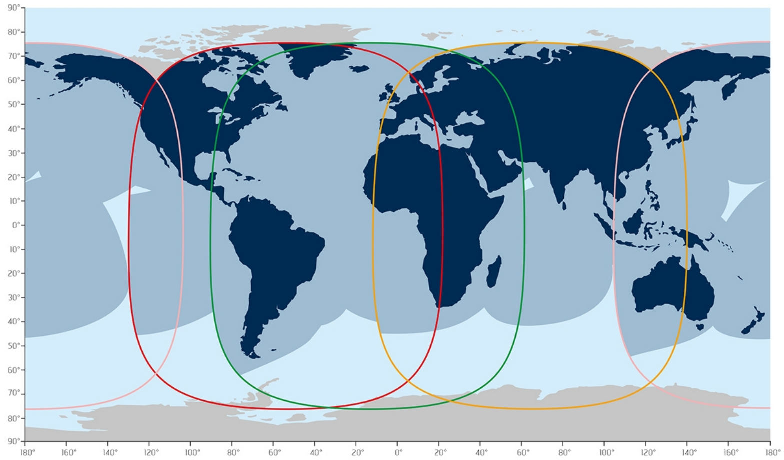


Figure 3: Approximate coverage of GEO Satellites.

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

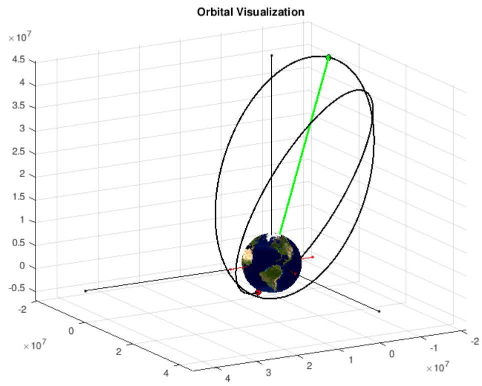
The parameters of the orbits analysed in the simulator are presented in Table 1.

	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

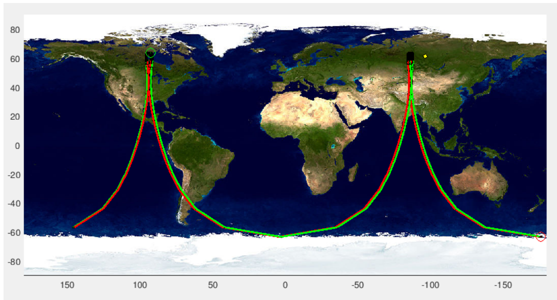
Table 1: Parameters of the considerated orbits

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

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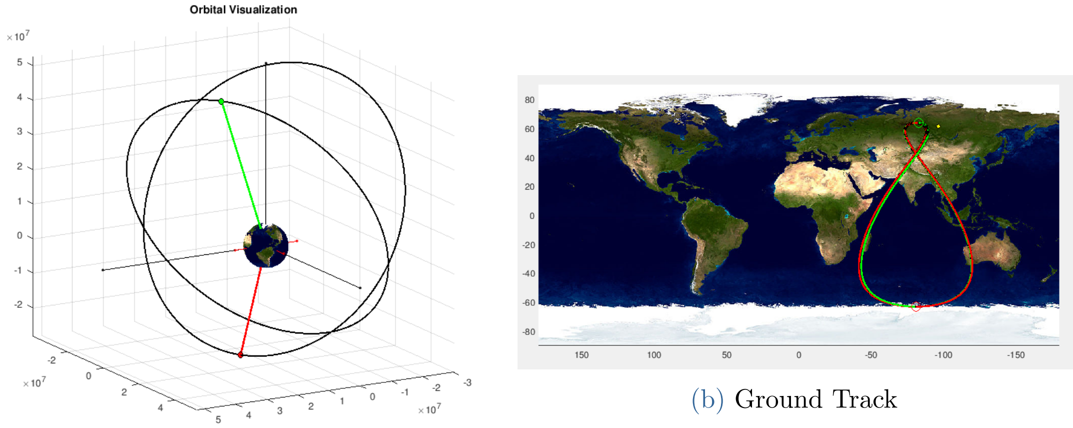

(b) Ground Track

(a) 3D Visualization

Figure 5: Graphical visualization of Tundra orbit

3.1 Communication Module

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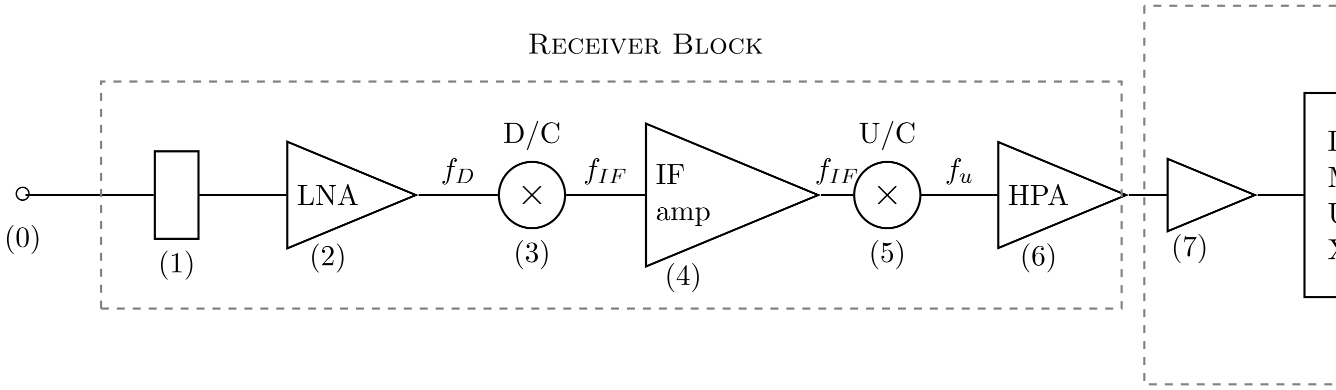
3.2 Payload



SECOND-ORDER NOISE SHAPER

3.2.1 Receiver Block

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3.2.2 Repeater Block

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3.3 Power Budget

3.3.1 Required Power

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3.3.2 Solar Panels specifications

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3.4 Weight Estimation

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4. Ground Segment

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4.1 Ground Station coordinates

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4.2 Ground Station requirements

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4.3 User requirements

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 [1] and reported in Table 2.

	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 2: 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 5.3.

$$g = \eta\left(\frac{\pi d}{\lambda}\right)^2 \qquad G = 10log\left[\eta\left(\frac{\pi d}{\lambda}\right)^2\right]\ dBi \tag{5.3}$$

The result for each antenna are in Table 3.

	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 3: 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 4. 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 4: 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 5.4 we obtain the plots in Figure 7 and Figure 8.

$$L_{rain} = kR^{\alpha} L_s r_p \tag{5.4}$$

The parameters in Equation 5.4 are calculated as in Equation 5.5.

$$\begin{aligned} k &= 4.21 \times 10^{-5} \cdot f^{2.42} \\ \alpha &= 1.41 \cdot f^{-0-0779} \\ L_s &= \frac{2km}{sin\theta} \\ r_p &= \frac{90}{90 + 4L_s cos\theta} \end{aligned} \tag{5.5}$$

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 5.6, 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.

$$L_{PL} = 20log\left(\frac{2\pi r}{\lambda}\right)\ dB \tag{5.6}$$

Using Equation 5.6 in each istant of the simulation, we obtain the plots in Figure 9 and Figure 10.

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 5.7, 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

$$p_{tx}^{1T} = [p_{HPA}]_{dB} - l_{mc} - l_{ftx} \tag{5.7}$$

$$p_{tx} = p_{tx}^{1T} + 10log(12) \tag{5.8}$$

Then the EIRP is calculated for Uplink and Downlink with the formula in Equation 5.9.

$$EIRP = G_{tx} + p_{tx} \tag{5.9}$$

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 5: 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 11 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 12 lists the different sections, depending on the type of mission the satellite is intended to accomplish, with their standard deviations; tables 13 and 14, instead, show the total cost depending on the mission type and the total cost per pound.

Regarding the cost per subsystem, Table 5 and Table 6 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 15 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 6: 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 7: 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:

$$Cost_{Total} = Cost_{Launch} + Cost_{Spacecraft} = \text{(Cri says: Mettere costo finale)}€ \tag{6.10}$$

7. Final considerations and conclusions

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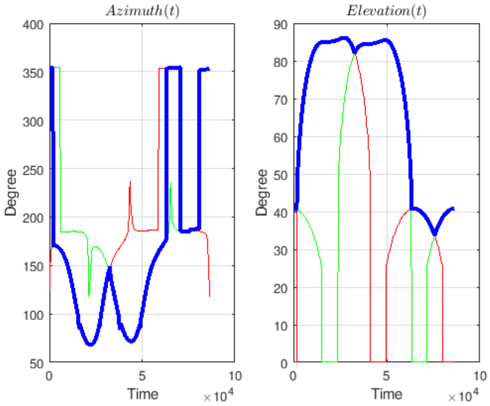
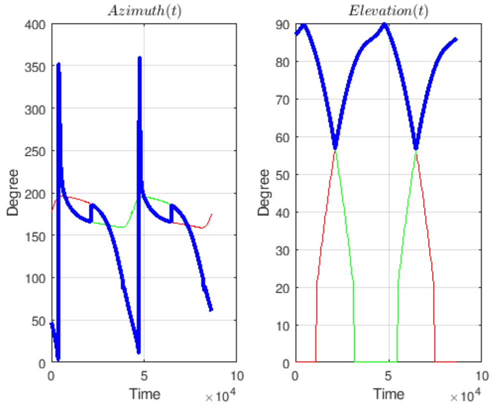
References

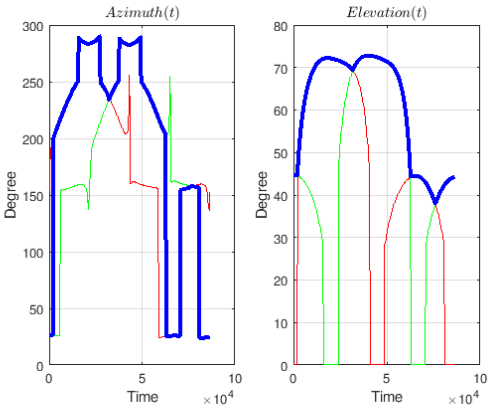
[1] L. J. Ippolito, *Satellite Communications Systems Engineering Atmospheric Effects, Satellite Link Design and System Performance.* Wiley, 2017.



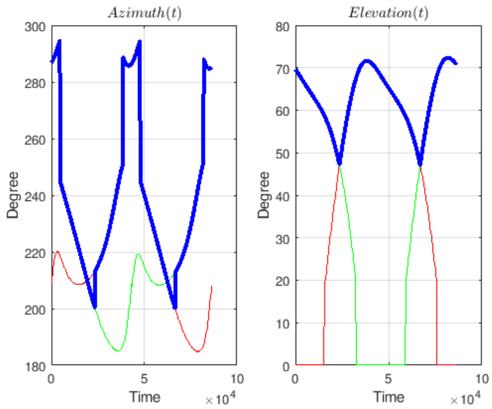
(a) Molniya, $Lat = 61°$ $Long = -75°$



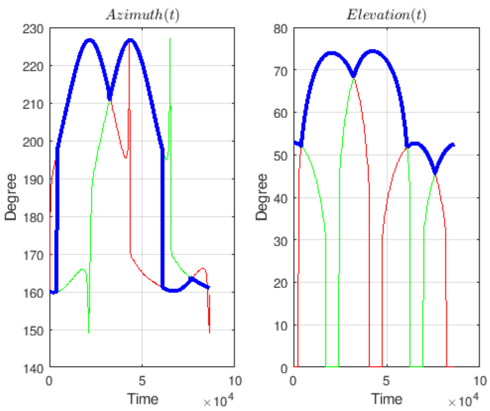
(b) Tundra, $Lat = 61°$ $Long = -75°$



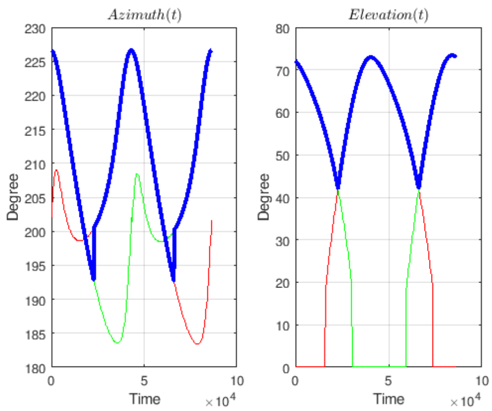
(c) Molniya, $Lat = 61°$ $Long = -130°$



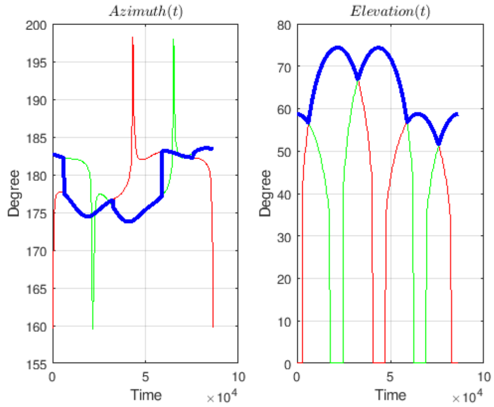
(d) Tundra, $Lat = 61°$ $Long = -130°$



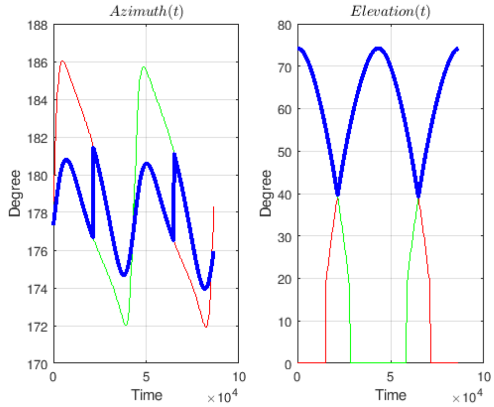
(e) Molniya, $Lat = 71°$ $Long = -130°$



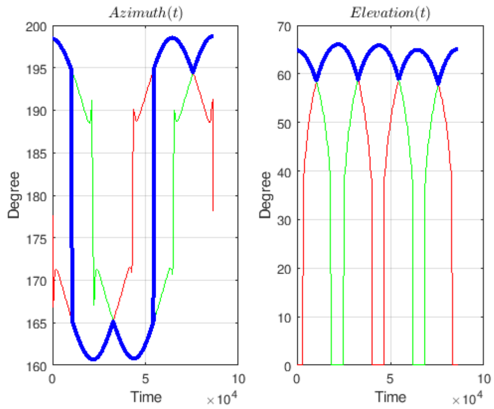
(f) Tundra, $Lat = 71°$ $Long = -130°$



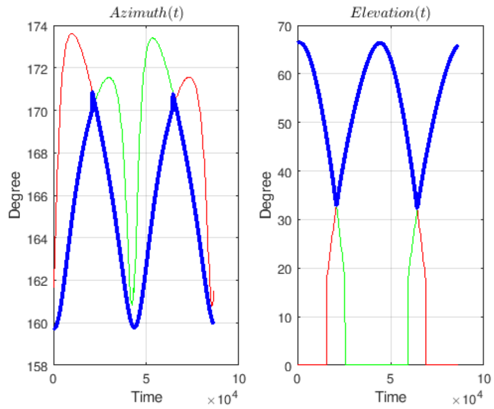
(g) Molniya, $Lat = 81°$ $Long = -75°$



(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

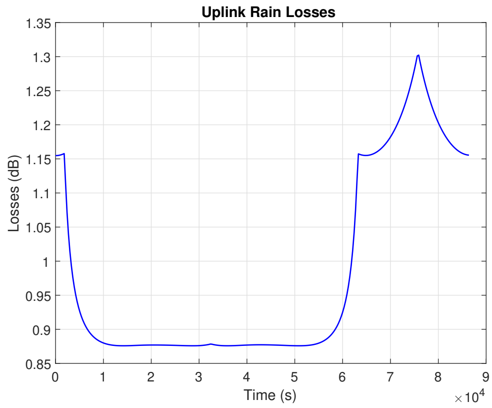


Figure 7: Variation of rain losses in Uplink over the time

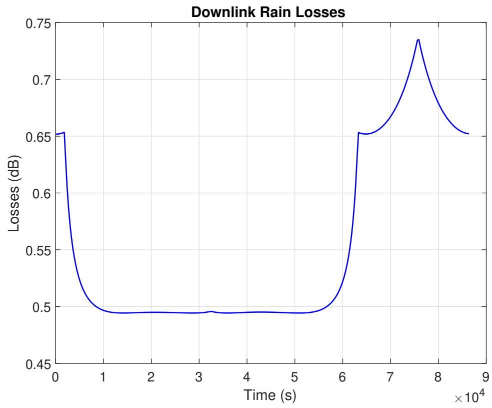


Figure 8: Variation of rain losses in Downlink over the time

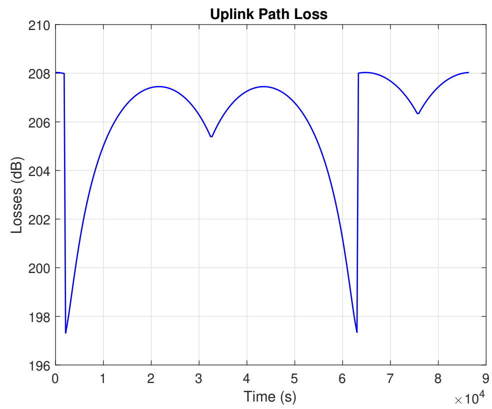


Figure 9: Variation of Path Loss in Uplink over the time

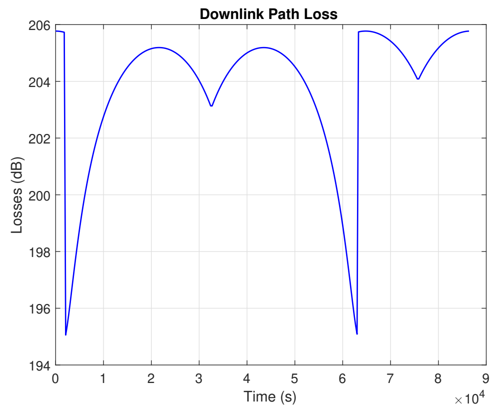


Figure 10: Variation of Path Loss in Downlink over the time

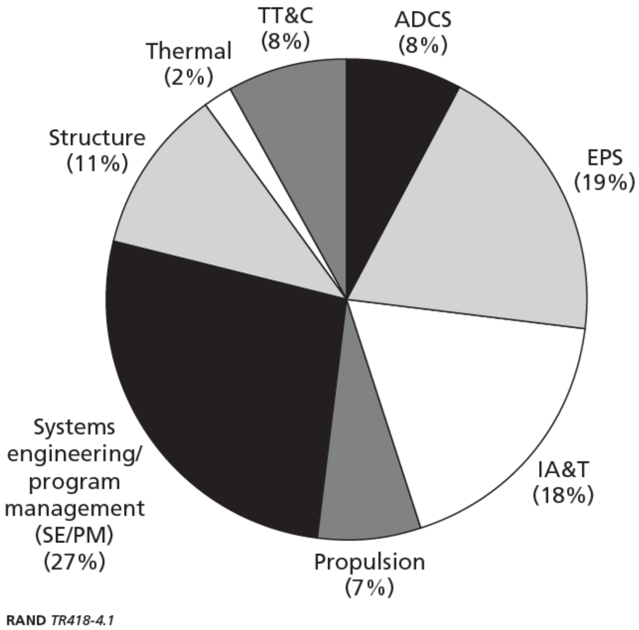


Figure 11: Communication spacecraft cost composition

	Average (%) (standard deviation)							
Cost	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 12: 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

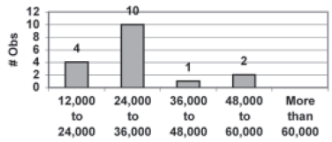


Figure 13: Total spacecraft cost

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

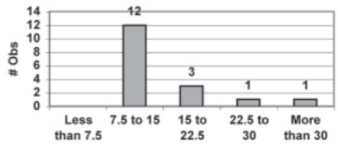


Figure 14: Total spacecraft cost per pound

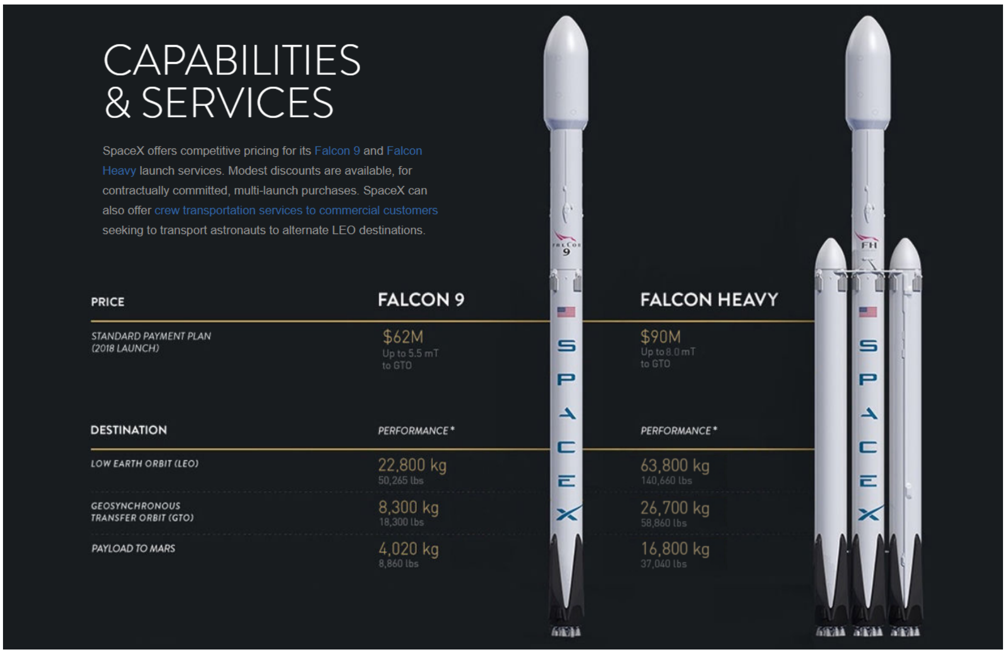


Figure 15: *SpaceX* price list